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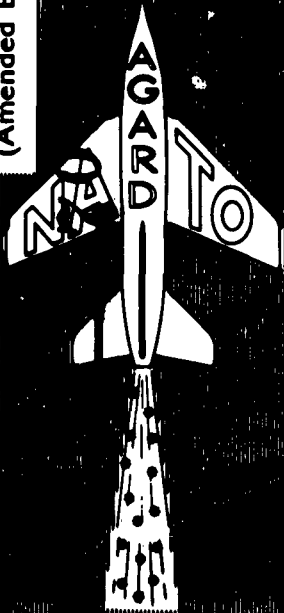
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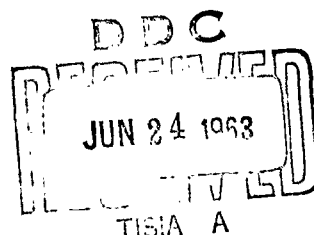
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REQUIREMENTS FOR AN AXIAL FATIGUE MACHINE CAPABLE OF FAST CYCLIC HEATING AND LOADING

by

H. P. van LEEUWEN & M. C. MUCUOĞLU



SEPTEMBER 1961

NORTH ATLANTIC TREATY ORGANIZATION
ADVISORY GROUP FOR AERONAUTICAL RESEARCH AND DEVELOPMENT

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NORTH ATLANTIC TREATY ORGANIZATION
ADVISORY GROUP FOR AERONAUTICAL RESEARCH AND DEVELOPMENT
(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

REQUIREMENTS FOR AN AXIAL FATIGUE MACHINE
CAPABLE OF FAST CYCLIC HEATING AND LOADING

by

H.P. van Leeuwen and Mahmut C. Mucuoğlu

September 1961

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SUMMARY

The object of the report was to investigate the requirements for an axial fatigue machine, capable of fast cyclic heating and loading. In order to evaluate the usefulness of existing equipment, various types of axial fatigue machines were studied with regard to the drive system, load capacity, frequency and accuracy. Additional studies concerned fast heating and cooling methods and their compatibility with the machines. Suggestions are made for modifications of existing equipment. Various solutions, using standard equipment, are recommended. Additional problems, such as extension measurement and temperature measurement, are briefly discussed.

SOMMAIRE

Le but du rapport est l'étude des spécifications pour une machine de fatigue capable d'effectuer des charges et des températures cycliques. Pour évaluer l'utilité des machines existantes une diversité de machines de fatigue axiales a été étudiée par rapport à leurs systèmes de mise en charge, charges maxima, fréquences et précisions. Des études supplémentaires sont faites concernant des méthodes de chauffage et de refroidissement rapides. Des modifications pour des machines déjà en existence sont suggérées. Plusieurs solutions, utilisant des appareils commerciaux, sont recommandées. Des méthodes pour la mesure des déformations et des températures sont discutées brièvement.

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REQUIREMENTS FOR AN AXIAL FATIGUE MACHINE CAPABLE OF FAST CYCLIC HEATING AND LOADING

H.P. van Leeuwen* and Mahmut C. Mucuoğlu†

1. INTRODUCTION

It has become a well-known fact that fast flying vehicles, supersonic aircraft and missiles are subject to heating. The heat emanates from two different sources, viz.

- (a) aerodynamic compression and skin friction at supersonic flight speeds,
- (b) chemical, and in the future also nuclear, energy release in the power plants.

The development of these vehicles has necessitated the study of materials properties at elevated temperatures and the development of pertinent testing equipment. Typical tests conducted so far include:

- (a) short time tensile and compressive tests at various rates of heating and loading,
- (b) short time creep and stress rupture tests,
- (c) high temperature hardness tests,
- (d) high temperature fatigue tests.

In most of these tests the temperature has been kept at steady levels. In practical cases, however, the temperature will show a time-wise variation during the life of the vehicle and also during a single flight. A typical example of a load-temperature history for a power plant structural component is presented in Figure 1, taken from Reference 14.

Dunsby, in his report to AGARD¹, has stressed the need for testing under conditions of cyclic temperature variation. He noticed that few of these tests had been conducted or were in progress at the time of his report. In cyclic heating tests load can be kept constant or can be varied simultaneously with the temperature. Possible tests, using cyclic heating as opposed to steady heating, are presented in Figure 2.

It may seem formalistic to include cyclic temperature heat treatment as an important feature in Figure 2. The cyclic temperature variation *per se* can, however, have important effects. Typical examples are the growth of polycrystalline uranium rods due to cyclic heating and the spheroidizing of carbides in steel by temperature cycling about 723°C.

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In principle the machine to be studied should be capable of steady heating as well as cyclic heating. In the present report, however, emphasis will be put on cyclic heating since this makes much greater demands on equipment than do constant heating and variation of levels of steady temperature.

2. REQUIREMENTS

Before putting down requirements it is necessary to elaborate on the types of testing envisaged.

The design of the machine may stem from the desire to simulate actual conditions. In this case heating frequencies related to ground-air-ground cycles as well as manoeuvres have to be considered. Likewise load frequencies related to ground-air-ground cycles, manoeuvres and gusts should be considered. It would be extremely helpful if the available frequencies were variable within a certain range. On the other hand the intent may be to study the fundamentals of the behaviour of structural materials under conditions of cyclic load and temperature variation. In this case it is desirable to distinguish between creep and fatigue and mix the two in various amounts. This requires an extremely low frequency, intermediate ones and a high frequency. Frequency variation within certain ranges is again desirable. High heating and cooling frequencies, however, may lead to undesirable side effects such as thermal stresses, with influences that are hard to evaluate. Acceptable requirements, for these and other reasons, should of necessity constitute a practical compromise between conflicting demands. On the basis of these considerations and those to be elaborated elsewhere in this Report, the following requirements can be listed:

- (a) The load capacity should be of the order of 10 tons in tension and compression.
- (b) The machine should be capable of load cycling at
 - a variable frequency of 0-10 cpm,
 - a fixed frequency not exceeding 100 cpm,
 - a fixed frequency of about 2400 cpm.
- (c) The machine should be equipped with control devices enabling the maintenance of load amplitude and mean load level under conditions of rapid creep and thermal expansion or contraction.
- (d) The machine should be provided with suitable heating equipment capable of reaching temperatures of the order of 2000°C.
- (e) The attainable heating and cooling rates should be of the order of 300°C to 600°C per minute.
- (f) The equipment should be capable of heating and loading standard ASTM tensile specimens with 2 in. (50.8 mm) gauge length, 0.5 in. (12.7 mm) width for sheet and plate and 0.5 in. (12.7 mm) diameter for rod and bar.
- (g) Accuracies of loading and heating should be in accordance with ASTM standards when and where applicable (e.g. E 4-36, E 8-46, E 21-43, E 22-41, E 150-59T, E 151-59T).

The following notes may be added:

- (a) Machines with capacities of the order of 5 tons and 25 tons can be useful in many cases and should not be overlooked.
- (b) In case the requirements (e.g. frequency) cannot be met by one and the same machine and modification would be unfeasible for some reason, thought should be given to employing a number of machines that together comply with the whole spectrum of requirements.
- (c) In some cases it can be desirable to control strain rather than load.
- (d) Development of a completely new machine should be proposed only when existing machines, even after some modification, are found to be unable to comply with requirements either individually or in combination with additional machines.

2.1 Load Capacity

In arriving at a definition of optimum load capacity it may be stated that the largest stress of interest would be halfway between the room temperature values of the 0.2% yield stress and the ultimate strength of the test material. At room temperature stresses below 1/3rd the ultimate strength are of no interest. Furthermore a material ceases to be interesting structurally when its strength has dropped below about 1/2 its room temperature value. Consequently 1/6th the R.T. ultimate strength may be considered the lowest stress of interest.

In Table I, the values of $\frac{1}{6}\sigma_u$ and $\frac{1}{2}(\sigma_{0.2} + \sigma_u)$ have been calculated for a number of representative materials. Since the ASTM specimens were selected a number of thicknesses of the flat specimen may be considered, for example 1 mm, 3.2 mm (1/8 in.), 6.4 mm (1/4 in.), 12.7 mm (1/2 in.) in combination with the standard 12.7 mm (1/2 in.) width and the standard 12.7 mm (1/2 in.) round specimen. Using the derived minimum and maximum stresses the desirable load ranges for each material and each specimen type can be calculated. These load ranges are presented in Figure 3. Considering that a fatigue machine is generally capable of accurately loading between 10% and 100% of its load capacity, a strong case can be made in favour of a machine having a capacity of 10 tons. Unfortunately this capacity would exclude most tests on magnesium alloy, all tests on graphite and some tests on steel, if standard ASTM specimens are used. The authors propose to adopt 10 tons capacity as a guiding figure without excluding machines of, say, 5 tons or 25 tons capacity.

2.2 Loading Frequency

The range of lowest frequencies was selected such as to be compatible with the attainable heating frequencies considering simulation of actual load and temperature histories like the one sketched in Figure 1. The fixed low frequency was arbitrarily selected with the intent of excluding fatigue phenomena from cyclic creep studies at this low frequency. The high frequency was selected in order to have fatigue predominate in tests at this frequency. On this basis alone a much higher frequency would, of course, have been desirable. A higher frequency would inevitably increase the power dissipation due to specimen damping. A study of power and control requirements in fatigue tests with cyclic temperature variation⁵⁵ showed the necessity of

restricting the upper frequency, as otherwise excessive requirements would be imposed on control systems, power sources and cooling equipment.

2.3 Load Control

For obvious reasons the loads on the specimen must be known and controlled during the test. Some machines impose predetermined strains rather than predetermined loads on the specimen, and the loads in these cases result from the mechanical properties of the specimen. Other machines work on the resonance principle and produce loads that are functions of the frequency and hence also of the specimen rigidity. In both these cases creep, thermal expansion and contraction due to cyclic heating will tend to alter the loads. The control system must cope with this situation.

2.4 Strain Control

When a notched specimen is fatigued at a fixed frequency and load amplitude the conditions in the immediate vicinity of the notch may be better described as constant-strain amplitude loading than as constant-stress amplitude loading. In comparing fatigue lives with those of smooth specimens, testing the latter at constant strain amplitude may provide a better basis. Tests of this nature conducted so far have shown the interesting relation $N^{\alpha} \epsilon_p = C$, between fatigue life and plastic strain amplitude, to hold for many materials with surprisingly similar values of the power α and the constant C . These considerations give ample incentive to control strain rather than load in fatigue testing.

At steady temperatures machines that impose strain amplitudes and mean strains rather than load amplitudes and mean loads are in an advantageous position. At cyclic temperature variation both types of machine need a sophisticated control system capable of distinguishing thermal expansion from mechanical strain.

2.5 Heating and Cooling

The upper temperature of 2000°C is felt to fulfil present and foreseeable requirements for a reasonably long time. Heating and cooling rates of 300 to 600°C/min were arrived at on the basis of Dunsby's study², which suggests such figures in view of the thermal stresses in cylindrical specimens.

2.6 ASTM Standards

These standards have an internationally accepted authority and present reasonable compromises between purely physical demands and requirements that can be met with the present state of the art.

2.7 Combining Machines

A machine meeting all the requirements will tend to be rather complex. There are obvious advantages in using a number of machines each complying with different requirements. This also offers the opportunity for laboratories to expand their capabilities bit by bit.

3. SUITABILITY OF EXISTING FATIGUE MACHINES

Fatigue machines, whether commercial ones or special laboratory designs, can be classified as to their drive systems as follows:

- (a) Mechanical
- (b) Hydraulic
- (c) Pneumatic
- (d) Electromagnetic
- (e) Thermo-mechanical
- (f) Magnetic-mechanical.

A survey of various machines is made in Appendix A and a summary of important parameters of representative machines is given in Table II.

3.1 Mechanical Drive

Mechanical drive systems can be subdivided into

- (a) Cranks and levers with or without weights
- (b) Power screws
- (c) Rotating eccentric masses and springs.

Fatigue machines belonging to these groups and apparently able to meet part of the requirements stated previously are:

- (a) The 15,000 lb Krouse machine and a dynamic creep machine of the type designed by Pao and Marin but with increased capacity
- (b) The Baldwin-Emery SR-4, Model FGT, machine and the Instron Model TT-CM-L machine
- (c) The Baldwin-Sonntag Model IV-20 V and less advanced models, and the Schenck PHQO and less advanced models.

3.1.1 The 15,000 lb Krouse Fatigue Machine (Fig.4)

With load coupling bars on a double-unit machine this machine is able to meet the load capacity requirement. It is less suited for slow simulation of actual load or strain histories with concurrent application of simulated temperature histories as sketched in Figure 1.

For load or strain cycling at a fixed frequency not exceeding 100 cpm, the present motor, supplying a fixed frequency of 800 cpm, will have to be replaced. Another motor must also be provided for load or strain cycling at a fixed frequency of about 2400 cpm.

The machine has excellent properties for strain cycling at a steady temperature. In this application the mean load control device has to be blocked and strain limiting devices of the type used by Anderson and Waldron⁶ may have to be provided*. It should

*Anderson and Waldron utilized a collar on the lower pull-rod striking plates bolted to the machine frame and held at distance with a spacer plate and shims (Fig.29).

be noted that this device limits the overall extension of the filleted specimen rather than the gauge-length strain. A simple relation will exist between the two when the specimen as a whole is at a uniform temperature. This is not likely to be the case with rapid heating and cooling. With cyclic temperature variation difficulties will occur due to strain concentration in hotter areas and because thermal expansion will require continuous readjustment of the strain limiting device.

The standard control equipment will meet the requirements for load cycling at a steady temperature. In the case of load cycling at cyclic temperatures the standard mean load control equipment will cope with creep and thermal expansion. The variation of specimen rigidity, however, requires that the mean load hydraulic piston should operate in tune with the loading lever; this, obviously, will prove to be difficult. One solution lies in automatic readjustment of the eccentric; but this also is rather difficult.

3.1.2 *The Dynamic Creep Machine (Pao and Marin)(Fig.5)*

The existing machine does not meet the requirements of load capacity and frequency. The basic design, however, has some possibilities. The design is not suited for simulation of actual load and temperature histories but is very well suited for load cycling at steady temperatures. An electric motor providing the two required fixed frequencies should be installed and resonance of the mean load lever must be avoided.

For strain cycling at uniform steady temperatures a strain limiting device could be used (see Fig.30). In the case of load cycling at cyclic temperatures, creep and thermal expansion of the specimen is taken up by rotation of the mean load lever. The specimen rigidity does not influence the load as long as the specimen remains much more rigid than the loading spring. The machine is less suited for strain cycling at cyclic temperatures.

3.1.3 *The Baldwin-Emery SR-4, Model FGT, and the Instron Model TT-CM-L Machines*

These machines are basically similar. Load capacity of the former is somewhat high, and the latter somewhat low. They can be applied to simulate actual load and temperature histories when feed-back controlled programming equipment is provided. It is possible to apply the machines in slow load cycling at steady and cyclic temperatures with the existing control equipment. The machines cannot provide the required high frequency.

The machines are also applicable in strain cycling at a steady temperature, using a commercial high temperature extensometer.

Difficulties arise with strain control at variable temperatures since measured strains have to be corrected for variable thermal expansion. In this situation the use of a dummy specimen is recommended. This is heated in such a way that the active specimen's temperature level, distribution and history are duplicated. The extensometer signal from the dummy specimen is then subtracted from that of the test specimen and the resulting signal can be used for the control of mechanical strain.

3.1.4 *The Baldwin-Sonntag Model IV-20 V (Fig. 6)* *and the Schenck Model PHQO (Fig. 7)*

The load capacity of the former is about right, that of the latter somewhat low. These machines are not well suited for simulation of actual load or strain and temperature histories.

The Sonntag machine with mean load programmer and the Schenck machine can be applied in load cycling at a low fixed frequency at steady as well as cyclic temperatures.

The machines are inherently suitable for load cycling at a high fixed frequency at steady as well as at cyclic temperatures. The Sonntag machine, however, should be provided with an electric motor of higher speed. Both machines can be equipped for strain control at uniform steady temperatures.

Strain limiting devices as shown in Figures 29 and 30 would be useful at low frequencies and uniform steady temperatures, but would not allow the smooth operation at high frequency required by the sub-resonance drive. A better solution would be to mount a high-temperature extensometer on the specimen. In the case of the Baldwin machine the extensometer would have to carry a strain transducer similar to those mounted on the torque bar of the mean load system*; with the Schenck machine it would have to carry control contacts similar to those mounted on the loading springs.

3.2 Hydraulic Drive

Hydraulic drive systems basically apply load rather than strain. They can be subdivided into

- (a) Generation of dynamic pressure
- (b) Regulation of pressure from a constant pressure source.

Fatigue machines belonging to these groups and apparently able to meet part of the requirements are

- (a) The Amsler pulsator, the Riehle-Los RL 30/40 DA pulsator and the G.M.R. pulsator
- (b) The Universal testing machine of the type designed by Bramer, Kahmann and Titus.

3.2.1 *The Amsler, Riehle-Los and G.M.R. Pulsators (Figs. 8, 9, 10)*

The Riehle-Los RL 30/40 DA has about the right load capacity. The load capacities of the other two machines are much too high.

These machines are not well suited for slow simulation of actual load or strain and temperature histories such as those sketched in Figure 1. They are inherently suitable for load cycling at fairly high and low frequencies, steady and cyclic temperatures, but have to be provided with electric motors able to meet the frequency requirements.

*Figure 6 shows an older type of machine applying helical springs instead of a torque bar. Furthermore, on the new model, the eccentricity of the rotating eccentric mass is adjustable while the mass rotates.

Strain cycling at uniform steady temperatures could be accomplished by using strain limiting devices such as those shown in Figures 29 and 30. A better but more complex solution would be to put control contacts on a high-temperature extensometer fixed to the specimen.

Strain cycling at cyclic temperatures would meet with increased difficulties.

3.2.2 *The Universal Testing Machine (Bramer, Kahmann and Titus)*

This machine, apart from the heating system (direct resistance), is a simple hydraulic loading device with a sophisticated control system incorporating a servo transfer valve, a load cell and electronic feed-back. The load capacity is somewhat high. The machine can be used for slow simulation of actual load and temperature histories when a suitable programmer is installed.

The machine is suitable for load cycling at a fixed low frequency at steady or cyclic temperatures.

Load cycling at a high frequency is not easily accomplished. For strain cycling at a steady temperature the function of the load cell can be taken over by a suitable high-temperature extensometer.

Strain cycling at cyclic temperatures is also difficult to accomplish. In principle a control device of the kind suggested for the screw-driven machines could be used (see Section 3.1.3).

3.3. Pneumatic Drive

Pneumatic fatigue machines are more or less similar to hydraulic fatigue machines. Machine manufacturers seem to favour hydraulic drives rather than pneumatic drives, however. The following subdivision can be made:

- (a) Generation of dynamic pressure
- (b) Regulation of pressure from a constant pressure source.

Machines able to meet part of the present requirements are:

- (a) The Lehr pneumatic fatigue machine
- (b) The ORNL strain cycling apparatus.

3.3.1 *The Lehr Pneumatic Fatigue Machine (Fig.11)*

The load capacity of this machine is much too high. It more or less resembles the G.M.R. pulsator. When provided with a suitable electric motor and a suitable control system it could be used for load cycling at high and low frequencies, at steady and cyclic temperatures.

Strain cycling at uniform steady temperatures and fixed frequencies would be possible using strain limiting devices.

3.1.4 *The Baldwin-Sonntag Model IV-20 V (Fig. 6)* and the *Schenck Model PHQO (Fig. 7)*

The load capacity of the former is about right, that of the latter somewhat low. These machines are not well suited for simulation of actual load or strain and temperature histories.

The Sonntag machine with mean load programmer and the Schenck machine can be applied in load cycling at a low fixed frequency at steady as well as cyclic temperatures.

The machines are inherently suitable for load cycling at a high fixed frequency at steady as well as at cyclic temperatures. The Sonntag machine, however, should be provided with an electric motor of higher speed. Both machines can be equipped for strain control at uniform steady temperatures.

Strain limiting devices as shown in Figures 29 and 30 would be useful at low frequencies and uniform steady temperatures, but would not allow the smooth operation at high frequency required by the sub-resonance drive. A better solution would be to mount a high-temperature extensometer on the specimen. In the case of the Baldwin machine the extensometer would have to carry a strain transducer similar to those mounted on the torque bar of the mean load system*; with the Schenck machine it would have to carry control contacts similar to those mounted on the loading springs.

3.2 Hydraulic Drive

Hydraulic drive systems basically apply load rather than strain. They can be subdivided into

- (a) Generation of dynamic pressure
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Fatigue machines belonging to these groups and apparently able to meet part of the requirements are

- (a) The Amsler pulsator, the Riehle-Los RL 30/40 DA pulsator and the G.M.R. pulsator
- (b) The Universal testing machine of the type designed by Bramer, Kahmann and Titus.

3.2.1 *The Amsler, Riehle-Los and G.M.R. Pulsators (Figs. 8, 9, 10)*

The Riehle-Los RL 30/40 DA has about the right load capacity. The load capacities of the other two machines are much too high.

These machines are not well suited for slow simulation of actual load or strain and temperature histories such as those sketched in Figure 1. They are inherently suitable for load cycling at fairly high and low frequencies, steady and cyclic temperatures, but have to be provided with electric motors able to meet the frequency requirements.

*Figure 6 shows an older type of machine applying helical springs instead of a torque bar. Furthermore, on the new model, the eccentricity of the rotating eccentric mass is adjustable while the mass rotates.

Strain cycling at cyclic temperatures would be hard to accomplish.

3.3.2 *The ORNL Strain Cycling Apparatus (Fig.12)*

The load capacity and the frequency of this machine are rather low. The machine is unique in so far as it provides free access to one end of the specimen. The basic design requires tubular round specimens. It would be possible, however, to modify the machine so that flat or solid round specimens could be used (Fig.12).

The machine was designed to perform slow strain cycling tests at uniform, steady temperatures, incorporating strain limiting nuts on the piston rod.

For load cycling tests a load sensing and controlling devices would have to be developed. The machine could then operate at a low frequency and at steady as well as cyclic temperatures. With a load programmer it could perform actual load and temperature history simulation tests.

Load or strain cycling at high frequencies and strain cycling at variable temperatures would not be easily accomplished.

It should be noted that the suggested modifications are, in fact, a complete redesign.

3.4 *Electromagnetic Drive*

Electromagnetic drive systems have the attractive feature that the electric current producing the magnetic force could be rather easily controlled to obtain the required load magnitude, frequency and wave form.

To meet a load capacity requirement of 10 tons a great amount of costly electric power would have to be provided. For this reason most designs rely on resonance to attain the required specimen loads. This automatically puts limits on the available frequencies. There are two possible types of resonance:

- (a) mechanical resonance
- (b) electromechanical resonance.

Machines operating on these principles are:

- (a) The Haigh fatigue machine

The fatigue machine incorporating Fransson's design

- (b) The Amsler Vibraphore 10 HFP 422.

3.4.1 *The Haigh Fatigue Machine (Fig.13)*

This machine just about meets the requirements for load capacity and fixed high frequency.

It is not well suited for slow simulation of actual load and temperature histories.

Load cycling at steady temperatures could be performed at a low fixed frequency using a modification of the type suggested by Forrest and Tapsell¹⁷ and at a high frequency using the machine without modification.

Automatic compensation for creep of the specimen, leading to unequal air gap widths above and below the armature, does not seem to have been provided yet on the standard machine. Forrest and Tapsell equipped their machine with such a device. It automatically pulled up or pushed down the top end of the specimen in case drift of the armature required such action. Control switches limited the extreme positions of the armature.

Load cycling at cyclic temperatures may be difficult to accomplish because due to thermal expansion and contraction of the specimen the mean air gap width between the magnets and armature will vary continuously (Fig.13).

Strain cycling will also be difficult to perform.

3.4.2 *The Fatigue Machine Incorporating Fransson's Design (Fig.14)*

This machine does not meet the requirements of load capacity (too low), fixed high frequency (too high) and specimen shape (tubular). A machine meeting these requirements could, however, be designed on similar principles. Such a machine would have to use a powerful electromagnet obviating the need for mechanical resonance. By feeding an electric current of the required magnitudes of amplitude and mean value, frequency and wave form to the magnet coil, load simulation tests as well as load cycling tests at fixed high and low frequencies could be performed.

Loads could be measured with a load cell in series with the specimen. The signal from the load cell could be used in a feed-back control system, correcting for creep, thermal expansion and other sources of error. A suitable high-temperature extensometer could perform the function of the load cell in strain cycling tests.

3.4.3 *The Amsler Vibraphore 10 HFP 422 (Fig.15)*

The load capacity of this machine is exactly right. Its frequency is much too high. The machine is not well suited for slow simulation of actual load and temperature histories.

In principle it would be possible to use the mean load controlling screw drive as an additional slow drive system in slow load cycling tests at steady or cyclic temperatures if a suitable control system would be added.

The machine could be used in fast load cycling tests at steady temperatures if the high frequency were acceptable. Fast load cycling at cyclic temperatures may meet with difficulties as the machine operates on the top of the resonance curve of the system and alterations of the specimen rigidity and specimen damping will impose severe requirements on the control system and power supply. Controlled strain cycling will also meet with difficulties. In principle the control system could be made to react to deformation of the specimen rather than of the dynamometer. This, however, requires far-reaching modification.

3.5 Thermo-Mechanical Drive (Figs.16 and 17)

In thermo-mechanical drive systems the loads result from restrained thermal expansion of either a heated specimen or heated parallel members. It is clear that the load variation cannot be separated from the temperature variation, which is very unsatisfactory. Machines having this type of drive will not be considered further in the present study.

3.6 Magnetic Drive

In magnetic drive systems two principles can be observed:

- (a) A reciprocating permanent magnet
- (b) Magneto striction.

Machines operating on these principles are:

- (a) The fatigue tester of the type designed by Danek and Achter (Fig.18)
- (b) The fatigue tester of the type designed by Neppiras (Fig.19).

Type (a) is a bending machine and was included only as a practical realization of the principle considered. It is clear that in order to obtain the required load capacity very strong and heavy magnets would have to be employed. An easier solution would be the electromagnetic drive already discussed.

Magneto striction fatigue testing as envisaged by Neppiras essentially requires extremely high frequencies and low loads. This excludes it from further consideration in this report.

4. SUMMARY OF MACHINE SUITABILITIES

The last column of Table II presents the applications of the machines considered.

In Table VII the ten different types of testing are enumerated and a selection is made of the machines that could be used for these tests. The machines are more or less listed in order of preference. The following conclusions can be drawn:

- (a) No machine is available yet that can perform all the tests.
 - (b) There are machines available that can perform *slow load and temperature simulation* tests when equipped with a suitable feed-back control system. These machines can also perform *slow load cycling* tests at a fixed frequency at steady or cyclic temperatures.
 - (c) There are machines available that can perform load cycling tests at a *high fixed frequency* and steady or cyclic temperatures. These machines are equipped or can be equipped with additional slow drive systems enabling them to perform load cycling tests at a *low fixed frequency* at steady or cyclic temperatures.
-

- (d) As regards *load cycling* a laboratory equipped with one machine of the type described in (b) above and another of the type described in (c) above could perform the desired tests. Examples: Baldwin-Emery SR-4, Model FGT, together with Baldwin-Sonntag Model IV-4V or Instron Model TT-CM-L together with Schenck Model PHQO. A Riehle-Los RL 30/40 DA could replace the second machine in both of the pairs mentioned above.
- (e) For controlled *strain cycling* tests a reliable high temperature extensometer is required. Many of the machines mentioned under (b) and (c), when equipped with such an extensometer, could perform the strain controlled counterparts of most of the load cycling tests mentioned.
- (f) For *strain cycling tests at uniform steady temperatures*, simple strain limiting devices can sometimes be used instead of high temperature extensometers.
- (g) For *strain cycling tests at cyclic temperatures* the extensometer system could be backed up by an extensometer on a dummy specimen subjected to the heating cycle only. This would enable the subtraction of purely thermal expansion and contraction.
- (h) It appears to be advantageous to develop a powerful electro-magnetic loading device equipped with a sophisticated control system and extensometer system so that all the tests can be performed on one machine.

5. HEATING METHODS

Heating equipment applicable to materials testing can be classified as follows:

Combustion furnace heating

Specimen inside the furnace (includes fluidized beds)

Specimen outside the furnace (includes pebble bed heaters).

Electrical resistance heating

Direct resistance

Resistance furnaces

- (a) gas atmosphere
- (b) vacuum atmosphere
- (c) liquid atmosphere
- (d) fluidized solids atmosphere

Incandescent lamps

Contact heaters

- (a) electric blankets
- (b) sprayed elements.

Electric arc heating

Direct arc

Indirect arc

- (a) radiative heat transfer (arc image)
- (b) convective heat transfer (plasma jet).

Electric induction heating

Direct induction

Indirect induction (induction furnaces).

*Electron bombardment heating**Solar furnace heating**Other means of achieving high temperatures.*

Short descriptions of the heating methods and the equipment are presented in Appendix II. Relevant information in condensed form is gathered in Table III and a summary of advantages and disadvantages is given in Table IV. Both tables are taken from Reference 59. On the basis of this information it can be concluded that the following heating methods are the most attractive:

For heating at accurately controlled steady temperatures

Electrical resistance furnace with atmosphere as required by test material.

For rapid (cyclic) heating

Direct high frequency induction
Incandescent lamps
Direct electrical resistance.

The power requirements for rapid heating can be roughly estimated if the following conditions are fulfilled:

A flat ASTM specimen 6.4 mm thick
A cosine function for the temperature distribution (see Appendix IV)
A maximum temperature of 2000°C
A heating rate of 600°C/min (10°C/sec)
The materials listed in Table I
Tungsten as test material because of its high melting point, high thermal conductivity and average specific heat per unit volume
Convective heat losses in still air
An emissivity of 0.5 (tungsten has 0.28 at 2000°C),

The power requirements then will not exceed the following values:

convective heat losses:	400 watt
conductive heat losses:	1700 "
radiative heat losses:	1900 "
heat absorption in specimen:	200 "
 Total power requirement:	 4200 watt

A suitable furnace for reaching steady temperatures of 2000°C will consume about 25000 Watt²⁹.

6. RAPID COOLING METHODS

Cooling methods can be classified according to the media utilized, viz.

Gas cooling

- Stagnant gas
- Forced convection
 - (a) in open air
 - (b) inside furnace

Liquid cooling

- Liquid cooled specimens
- Liquid cooled clamps

Fluidized solids cooling

- Molten solid
- Powdered solid

In Appendix III a survey is made of actual tests reported in the literature and in Appendix IV cooling times achievable with various media are calculated for a practical case involving Nimonic 80 A as test material and temperatures between 900°C and 20°C.

It appears that under average conditions the combination of water-cooled clamps and still-air cooling is the most suitable in view of the cooling rates required. There may be cases (e.g. high thermal conductivity of specimen) where the conductive heat flow is too large. The specimen should then be partially insulated from the clamps. There may also be cases (e.g. thick specimens and low initial temperatures) where the attainable cooling rate is too low. In these cases forced convection should be added. When the specimen requires protection from oxidation a non-reactive gas can be used. The gas can be circulated at the speed required by the desired cooling rate.

7. STRAIN MEASUREMENTS

The most direct method of strain measurement would be to bond resistance strain gauges to the specimen. Unfortunately this method is restricted to relatively low temperatures (below 600°C). Furthermore, reliability of measurement, especially in case of static strains, is also rather low. In addition the applied gauges can obstruct the heat flow with radiant heating and convective cooling.

A method of measuring extension which has been most satisfactory at high temperatures involves the use of micrometer microscopes⁴⁸ sighting directly on reference marks indicating the gauge length of the specimen. A stroboscopic light source is operated at the frequency of the machine, showing the reference marks consistently at the same position of their vibration cycle. The dynamic strain is measured through determination of the travel ranges of the two reference marks. Subtraction yields the dynamic strain range of the specimen. Modifications of this method involve the attaching of strips, wires and thin tubes to the specimen shoulders. These attachments meet half-way along the specimen gauge length. The relative travel of reference marks on these attachments indicates specimen strain. Unfortunately the attachments are liable to influence specimen temperature in some cases (e.g. radiant heating, forced air cooling). Furthermore their thermal expansion will impair accuracy of measurement. It should be noted also that this method is less suitable for control purposes where electrical signals indicating strain are required.

Other methods of measuring the strain employ rods or tubes and rods suspended from bridges clamped to the specimen at the ends of the gauge length in order to transfer the motion outside the heated environment. Various methods are used to measure the relative travel of the strain transfer rods (or tubes). Such methods involve dial gauges, the well known Martens mirror system and electrical strain transducers working on the principles of variable resistance, inductance or capacitance. The static and the dynamic components of strain can be separated by mechanical means or by electrical means.

The use of dashpots together with dial gauges is reported in Reference 50. Guarnieri and Miller⁴⁹ describe an extensometer where the strain transfer rods load cantilever beams in bending. SR-4 strain gauges are bonded to the beams and indicate their deflections. The deflections are calibrated against specimen extensions by the use of micrometers. Extensometers employing strain transfer rods and microformers are commercially available from many sources.

With rapid heating and cooling the strain transfer rods should be kept outside the influence area of the heating coils, incandescent lamps and cooling air stream. Thermal expansion and contraction would otherwise lead to erroneous results. Also it may be advantageous to utilize Invar or other low thermal expansion materials because it would be difficult to obtain perfect shielding.

With direct resistance heating the strain transfer rods should be electrically insulated from the specimen. Thermal insulation will, of course, be advantageous in all cases, since it protects the strain transfer rods from heating and also prevents their influence on the specimen temperature distribution.

It should be noted that the extension measured is the sum of specimen strain and thermal expansion. It has already been suggested that a dummy specimen fitted with an extensometer and subjected to the same heating cycle as the active specimen be used, in order to separate mechanical and thermal expansion.

8. TEMPERATURE MEASUREMENTS

Many methods are available for the measurement of temperature^{26, 28}. Such methods involve:

Thermal expansion of gases, liquids and solids
 Change of electrical resistance of metals and semi-conductors
 Generation of an e.m.f. in a circuit of dissimilar metals
 Intensity of radiation emitted by a heated body
 Nuclear resonance in chemical compounds
 Melting of special mixtures of minerals
 Colour change of temperature indicating paints.

Without going into detailed discussion it can be stated that for the present purpose thermocouples and radiation pyrometers are the most suitable. Well known thermocouples are the following:

<i>Thermocouple</i>	<i>Average sensitivity (mV/°C)</i>	<i>Temperature limit (°C)</i>
Copper/Constantan	0.052	500
Iron/Constantan	0.056	950
Chromel/Alumel	0.041	1100
90 Pt-10 Rh/Platinum	0.0116	1500
87 Pt-13 Rh/Platinum	0.0104	1500

Thermocouples with higher temperature limits are becoming available. For instance:

<i>Thermocouple</i>	<i>Average sensitivity (mV/°C)</i>	<i>Temperature limit (°C)</i>
Iridium/60 Ir-40 Rh	0.005	2000
Tungsten/Iridium	0.020	2000
Tungsten/W-Re	0.016	2500
Mo Si ₂ /Molybdenum	0.014	1800

These thermocouples suffer from drawbacks such as brittleness, oxydation, etc. Also such materials tend to deteriorate when used for long times at high temperatures. It is suggested, therefore, that the application of thermocouples for lengthy use be limited to temperatures up to 800°C in the case of chromel/alumel and up to 1200°C in the case of platinum-rhodium/platinum thermocouples. For short time use, as in calibration of radiation pyrometers, the temperature limits may be set higher and some of the newer thermocouples may be used.

Care should be taken to provide close contact between the hot junction and the specimen. If the bead of the hot junction is clamped or spotwelded to the specimen the danger that bead temperature and specimen temperature will differ is present with all of the heating methods recommended. An advantageous solution is to spotweld the two wires to the specimen individually. In this case the hot junction temperature will be identical with the specimen temperature. The interposition of specimen material at the junction will not affect the thermal e.m.f. provided that the interposed material is at uniform temperature (basic law of thermocouple circuits).

However, spotwelding should be rejected in certain cases, e.g. with smooth specimens where the spotwelds can initiate premature failure. A satisfactory compromise would be to tie the hot junction of the thermocouple to the surface of the specimen, using a small radiation shield attached to the hot junction in order to protect it from direct radiation.

In the case of induction heating and direct resistance heating an additional problem is posed by h.f., a.c. or d.c. pick-up. High frequency and alternating current necessitate the use of filters in the measuring circuit. Direct current can be avoided by proper positioning of the spotwelds. In order to restrict heating of the length of wire between hot and cold junctions by induced currents, use can be made of extremely thin wires embedded in magnesium oxide inside a metal tube of small outer diameter. It can be shown that when the wire diameter becomes less than twice the skin thickness parameter in induction heating, the wire will experience only a small temperature rise⁵⁹. Considering that at a frequency of 10^6 Hz the skin thicknesses with chromel and alumel will be about 0.3 to 0.4 mm and that thermocouple wire 0.1 mm thick is available, no trouble need be experienced in this respect.

For temperatures above 1000°C , the total radiation pyrometer is suitable, the emitted radiant energy being utilized to measure the temperature. The emitted energy is focussed on a sensitive thermopile with lenses. Then the temperature rise of the thermopile, measured in millivolts, is calibrated against temperature. Frequent calibration of the radiation pyrometer is necessary for accurate measurement and control. A problem with the radiation pyrometer is posed by the specimen emissivity (quotient of specimen radiant energy and black body radiant energy at equal temperatures). The emissivity should be known in order to obtain accurate measurement and control. It is possible to calibrate the total radiation pyrometer against thermocouples on a pilot specimen, provided that the emissivity will not vary from one specimen to another or change with time. A pyrometer suffering less from this drawback is the two-colour radiation pyrometer. It measures the ratio of intensities of radiation emitted at two different wave lengths, which is a temperature-dependent variable. But since most structural materials radiate in almost the same way as grey bodies (emissivity independent of wave length) the emissivities will not seriously affect this ratio.

9. CONCLUSIONS

- (i) At present there is no machine available complying with all the requirements set forth in the present report.
- (ii) Machines are available that can perform slow simulation tests of actual load and temperature histories. These machines can also perform load cycling tests at low fixed frequencies and at steady as well as cyclic temperatures.

- (iii) Other machines are available that can perform load cycling tests at high fixed frequencies and at steady as well as cyclic temperatures. These machines are equipped or can be equipped with an additional slow drive system for performing load cycling tests at low fixed frequencies and at steady as well as cyclic temperatures.
- (iv) Strain control as opposed to load control can be effectuated at steady uniform temperatures with simple strain limiting devices on some of the machines.
- (v) A better method of strain control would require an extensometer with strain transfer rods and electrical strain limiting switches or preferably electrical strain transducers.
- (vi) For strain control at cyclic temperatures a system is suggested in which a dummy specimen is fitted with an extensometer and subjected to the same heating cycle as the active specimen in order to separate the thermal expansion and mechanical strain of the active specimen.
- (vii) For load (strain) and temperature history simulation tests a suitable feedback programming and control system should be designed.
- (viii) The best heating methods involve electrical resistance furnaces for steady heating and high frequency induction, and incandescent lamps or direct resistance for temperature cycling.
- (ix) The best cooling method involves water-cooled specimen clamps with a stagnant gas atmosphere, if necessary augmented with forced convection or retarded by partial insulation.
- (x) The best methods of temperature measurement involve thermocouples at temperatures up to about 1000°C and radiation pyrometers at higher temperatures.
- (xi) Under present conditions tests can be performed using combinations of machines designed to perform as in (ii) above together with machines as indicated in (iii) above. Examples of machines the first type are the Baldwin-Emery SR-4, Model FGT, and the Instron Model TT-CM-L; examples of machines of the second type are the Baldwin-Sonntag Model IV-4 V with P 10-R programmer, the Schenck Model PHQO and the Riehle-Los Model RL 30/40 DA.
- (xii) It appears to be advantageous to develop an electro-magnetic machine able to comply with all the present requirements.

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APPENDIX I

SURVEY OF EXISTING AXIAL FATIGUE MACHINES

Existing fatigue machines can be classified as to their drive systems as follows:

- A. Mechanical
- B. Hydraulic
- C. Pneumatic
- D. Electro-magnetic
- E. Thermo-mechanical
- F. Magneto-mechanical.

A summary of representative machines is given in Table II. It should be noted that only brief descriptions of the machines and their working principles are given in the present report. At least one machine of a representative character has been studied from each category. In some cases, however, it has been considered worthwhile to mention more than one machine in some of the categories. In describing the machines, load capacities and frequencies have been given, in ranges, for commercial machines of various sizes. This has not always been possible for machines that have been developed by research institutes and laboratories. In these cases figures have been estimated from test results produced with the machines. Any modification done on a standard machine by a research institute or laboratory has been noted if it is of value to the present study.

A. AXIAL FATIGUE MACHINES WITH MECHANICAL DRIVES

Axial fatigue machines, with mechanical drives, embrace one of the most widely used groups of machinery in the field of fatigue testing. They are relatively inexpensive, easy to maintain and simple to operate. They can be divided into three groups according to their type of loading, as follows:

- 1. Cranks and levers with or without weights
- 2. Power screws
- 3. Rotating eccentric masses and springs.

A.1 Axial Fatigue Machines, Mechanically Driven by Cranks and Levers with or without Weights

A.1.1 Krouse Fatigue Testing Machine^{4,5,6,51}

As can be seen from Figure 4 a load lever is actuated by a variable-throw crank. Flexure plates are used for pivoting the lever arm and transmitting the variable force to the specimen in a ratio of about 10 to 1. Constant mean load is applied to the specimen and maintained by a hydraulic device functioning through an electronic circuit. Older machines apply mean load by a hand-actuated power screw. Load capacities range from 2.3 tons to 46 tons (5,000 - 10,000 lb), and frequencies from 1500 to 500 cpm. The machines are deadweight calibrated to 1% of load or 0.2% of capacity. Guaranteed accuracy is published as 2% of load or 0.2% of capacity. It should be noted that the

load capacity can be doubled by loading one specimen via load coupling bars on a double-unit machine.

Without the control system the machine would apply constant mean strain and strain amplitude to the specimen. The control system senses the deflection of the load lever, which is a function of maximum and minimum loads on the specimen. Deviations from the preset values are corrected by pulling up or pushing down the specimen with the hydraulic device. This essentially provides mean load control. Large variations of specimen rigidity due to cyclic heating will require operation of the hydraulic system in tune with the loading lever or automatic corrections of the crank throw. This, presumably, will prove to be difficult.

For the present application the 6.8 tons (15,000 lb) machine seems most advantageous. Unfortunately its frequency is 800 cpm. Modifications providing frequencies of about 100 and 2400 cpm do not appear to be difficult. For instance, a 5,000 lb capacity, 1000 cpm Krouse machine was modified by W.F. Anderson and C.R. Waldron of Atomics International, North American Aviation, Inc. to allow testing in the range from 0 to 15 cpm. A 3/4 hp electric motor and a 20:1 reduction gear were used in this low frequency drive system⁶. The machine can be provided with a variable speed unit¹¹.

A.1.2 Dynamic Creep Testing Machine¹¹

The machine, as sketched in Figure 5, was designed and developed by H. Pao and J. Marin, of the Pennsylvania State College, for dynamic creep tests.

The specimen is subjected to a fluctuating load consisting of a mean static load and an alternating load and is mounted in series with a dynamometer and loading spring. The mean static load is produced by a dead weight and a lever. The alternating load is produced by an eccentric, driven by a synchronous motor, pulling at the spring. The machine essentially is a controlled load device. When used as a static creep testing machine, it has a maximum load capacity of 1.13 tons (2500 lb); as a dynamic creep testing machine or as a fatigue machine the capacity is considerably lower, i.e. about 0.27 tons (600 lb) at 1800 cpm.

It should be possible to build a machine working on the same principle but having an increased load capacity and a variable speed drive. However, resonance of the lever and weight will have to be avoided.

A.2 Axial Fatigue Machines, Mechanically Driven by Power Screws

A.2.1 Baldwin Emery SR-4 Universal Testing Machine, Model FGT⁷

This machine is capable of testing specimens in tension, compression, creep, relaxation and fatigue.

The specimen is fixed between two platens, the top platen being mounted on two round columns. The bottom platen applies strain to the specimen by moving up or down a reversing power screw driven by a variable speed motor. The speed control is through an electronic valve system (thyatron tubes) and is capable of maintaining constant speed from zero to full load.

A Baldwin SR-4 Universal load cell incorporated in each column provides the means of accurate load measurement. The load is indicated on a dial by a servo-motor driven pointer. By means of upper and lower limit control knobs the load can be kept constant as in a creep test or made to cycle between an upper and a lower limit. Application of a Baldwin extensometer and stress-strain recorder provides the means to conduct constant strain (relaxation) tests or strain-cycling tests.

The machine has a 23 tons (50,000 lb) load capacity. The frequency in load cycling depends on the selected strain rate, the specimen gauge length, stiffness and maximum load but can be estimated as ranging from 0 to 45 cpm. Available strain rates range from 0.6 to 230 mm/min. and load accuracy is guaranteed as 0.5% of load or 0.1% of scale in the high load ranges and 0.75% of load or 0.15% of scale in the lowest load range.

A.2.2 Instron Testing Machine, Models TT-CM and TT-CM-L¹²

Instron machines operate on the same principle as the above-mentioned Baldwin machine. The specimen is mounted between an upper fixed cross head and a lower moving cross head. The latter is operated vertically by means of twin screws in a special design to eliminate back lash. Load is measured by a load cell between the specimen and the upper cross head. The versatile control device allows tension, compression, creep, relaxation and fatigue testing. Selection between load and strain control can be made. For the present application the Models TT-CM and TT-CM-L seem to be the most useful. Load capacities of these machines amount to 5 tons. Strain rates range from 0.5 to 500 mm/min for the TT-CM machine and from 0.05 to 50 mm/min for the TT-CM-L machine.

A.3 Axial Fatigue Machines, Mechanically Driven by Rotating Eccentric Masses and Springs

A.3.1 Sonntag Fatigue Machine^{4,6,9,10,52}

A schematic diagram of a Sonntag Fatigue Machine is shown in Figure 6. Basically these machines apply repeated load rather than repeated deflection.

Constant mean load is applied by means of a screw which transmits load to the bottom platen of the test stand through springs. Spring deflection is measured by means of dial gauges and controlled through limiting switches.

Dynamic load is produced by a mechanical oscillator driven through flexible couplings by a synchronous motor. The oscillator is a rotating screw and a micrometer calibrated mass is attached to its end. The position of the mass is calibrated to indicate the dynamic load. The centrifugal force produced by this revolving eccentric mass is transmitted through a frame to the test piece and the horizontal component of the centrifugal force is absorbed by flexure plates attached to the oscillating frame.

Apart from applying mean load, the springs, attached to the lower end of the frame, oppose inertia forces that are produced in the oscillating frame during the operation. Spring forces are calculated and calibrated to exactly equal the inertia forces, so that only the centrifugal force arrives at the specimen. A load cycle counter is attached to the machine which stops when the specimen fails.

These machines are built with various preload and dynamic load capacities and have a constant operating speed of 1800 cpm in the case of the Baldwin machines, 3600 cpm in the case of those developed by Lazan⁴⁸ and 1800 to 5600 cpm in the case of the machines developed by Taira⁵⁰. As an example of the load capacities, those of the following Baldwin machines can be mentioned:

Model	Capacity (tons)	Max. alt. load (tons)	Max. static load (tons)	Max. strain amplitude (mm)
Baldwin SF-01-U	0.200	0.100	0.100	12.5
Baldwin SF-1-U	1.000	0.500	0.500	9.0
Baldwin SF-10-U	5.000	2.500	2.500	6.0

Another type of Sonntag fatigue machine was developed, Model SF-20-U, testing specimens in a horizontal position⁹. Constant mean load is applied by a hydraulic system as in the case of the Krouse fatigue machine. Dynamic load is produced by a rotating eccentric mass. The machine has 4.5 tons preload and 4.5 tons dynamic load capacity, and operates at 1200 to 1900 cpm.

A newer development of the Baldwin-Sonntag machines is presented in the Multi-Range fatigue testers designated as the IV series, and available in six capacities¹⁰. In the three high capacity machines mean load application and inertia force compensation is provided by a torque bar and power screw assembly. Mean load is electronically controlled using a transducer sensing the mean deformation of the torque bar. In the low capacity machines mean load is applied by dead weight on a lever able to produce tensile as well as compressive loads. Dynamic load is applied as before. Means can be provided to adjust dynamic load on a running machine (symbol V in the model number). Most of these machines operate at a frequency of 1200 cpm but smaller types are available with a speed of 1800 cpm (symbol F in the model number). Relevant figures on the six machines are as follows:

Model	Capacity (tons)	Max. alt. load (tons)	Max. static load (tons)	Max. strain amplitude (mm)
IV-120(V)	54	27	27 (54)*	9.5
IV- 50(V)	23	11.4	11.4 (23)*	9.5
IV- 20(V)	9	3.6	5.4 (9)*	9.5
IV-4 (F)	1.8	0.9	0.9	9.5
IV-1 (F)	0.45	0.23	0.23	9.5
IV-02 (F)	0.09	0.045	0.045	9.5

*Applies to a machine with the symbol V in the model number and with the alternating load mechanism not in operation.

Load accuracy is claimed as 2% of load or 0.4% of capacity. For the Model IV-20V machine a programmer (P-10R) is available which programs mean and alternating loads in both magnitude and number of cycles. Consequently a machine thus equipped can apply slow cyclic loads with the eccentric mass not rotating^{10,52}.

A.3.2 Schenck-Erlinger Pulsator^{4,5,13}

A sketch of a Schenck-Erlinger pulsator is presented in Figure 7. Essentially the machine applies fluctuating loads rather than strains.

The dynamic load produced by a rotating invariable eccentric mass is transmitted to the specimen by a helical spring. A constant mean load is applied by a power screw and is transmitted to the specimen by a second helical spring concentric with the first one, but of smaller diameter. The power screw is actuated by an electric motor and a chain drive. Since the electric motor is reversible, it provides a means of conducting low frequency fatigue tests with the eccentric mass not rotating.

The quantities sensed and maintained by the control system are the extension ranges of the two springs. In the case of the high frequency drive system a deviation from the preset value produces an electric current operating a rheostat which feeds more or less current to the field coils of the h.f. drive electric motor. This raises or lowers its rpm and hence the applied dynamic load. The system operates on the climbing part of the resonance curve. In Reference 55 the behaviour of a typical Schenck machine was found to be satisfactory as to its response to variations in specimen rigidity and damping due to cyclic heating. For control of mean load the conventional extension-limiting switch system is used.

Standard machines are available with either mean load control or additional slow drive system. They can, however, be modified to incorporate both systems. In a newer development of these machines⁵³ both facilities are available through the use of three separate electric motors for the h.f. drive, mean load control and l.f. drive. The Schenck firm also produces a series of machines having an additional l.f. hydraulic drive system⁵⁴. Relevant figures for the Schenck machines are given overleaf.

B. AXIAL FATIGUE MACHINES WITH HYDRAULIC DRIVES

Machines in this category are, basically, ordinary tensile testing machines, equipped with auxiliary apparatus to apply alternating loads. They can be divided into two groups according to their type of loading, as follows:

1. Generation of dynamic pressure
2. Regulation of pressure from a constant pressure source.

Machines of this type have a relatively large loading capacity, and slow speed. The generation of a dynamic pressure is generally accomplished with conventional piston-pumps. Load regulation can take two forms. In the first, two constant stroke pumps are employed that operate with delivery curves that can be shifted out of phase. When the relative phase angle equals zero, net performance is maximum; when the relative phase angle equals 180°, net performance is zero. The second form of load regulation employs a variable-stroke piston pump. Hydraulic pulsators apply predetermined loads

Performance Data for the Schenck Fatigue Machines

Model	Fast drive system				Slow drive system			
	Max. total load (tons)	Max. alt. load (tons)	Nominal frequency (cpm)	Max. strain amplitude (mm)	Max. total load (tons)	Max. alt. load (tons)	Nominal frequency (cpm)	Max. strain amplitude (mm)
Standard machines with automatic mean load control but without slow drive								
PHMN	2	1	2600	5	-	-	-	-
PHQN	6	3	2400	5.5	-	-	-	-
PHTN	20	10	2200	6	-	-	-	-
PHXN	60	30	2000	7	-	-	-	-
Standard machines with additional slow drive but without automatic mean load control								
PHMD	2	1	2600	5	2.4	2	up to 40	15
PHQD	6	3	2400	5.5	7.2	6	up to 40	15
PHTD	20	10	2200	6	25	20	up to 40	20
PHXD	60	30	2000	7	72	60	up to 40	20
Special machine with automatic mean load control and additional slow power-screw drive								
PHQI	6	3	2400	5.5	6	6	up to 30	15
Special machine with automatic mean load control and additional hydraulic slow drive								
PHXI	60	30	2000	6	60	36	up to 30	10
Special machines for large displacements and program loading with automatic mean load control and additional hydraulic slow drive								
FBON	2.6	1	500-4500*	25	3	1.6	up to 100	40
FBRN	8	3	400-3600*	32	10	5	up to 100	50
FBNV	26	10	350-2600*	40	30	16	up to 100	63

* frequency variable by altering eccentric mass.

Load accuracy for these machines is claimed as 0.6 to 1% for the fast drive and 1 to 3% for the slow drive.

The Schenck firm also produces a series of vertical fatigue machines basically similar to the Baldwin-Sountag type IV machines. These will not be discussed.

rather than predetermined strains. The quantities sensed by the control system are the hydraulic pressures related to maximum load, minimum load and preload. As a consequence, measurements have to be corrected for inertia loads of moving machine parts.

B.1.1 Amsler Hydraulic Pulsator (old type)^{4,5}

A schematic drawing of this machine is presented in Figure 8. A regular Amsler tensile testing machine is equipped with an additional hydraulic system to apply fluctuating loads.

The pulsator mechanism consists of a rotating crank which applies oscillating motion to two pistons working in two oil cylinders. These cylinders are connected to the main cylinder of the testing machine. Oil flow is regulated by altering the angular spacing of the pistons, so that dynamic load applied by the pulsator is varied from zero to maximum value. Constant minimum load is applied by the machine before the dynamic hydraulic system is operated and is automatically kept at its preset value by hydraulic means. Maximum load is not controlled automatically.

The load capacity amounts to 50 tons. Operating speed is between 125 to 600 cpm. Load accuracy is guaranteed to be 3% of load after correction for inertia loads.

The Amsler firm now produces a more advanced model where the stroke of the piston pump is varied through an adjustable four-bar mechanism, and a second load cylinder is provided for testing with compressive mean loads.

B.1.2 Losenhausen Hydraulic Pulsator, Model UHS^{4,5,16}

A diagram of the Losenhausen pulsator is presented in Figure 9. Variable pressure is applied by means of a piston pump actuated by an oscillating lever which is driven by a crank. Load can be varied by changing the stroke of the drive. This is accomplished by shifting the piston and cylinder relative to the fulcrum of the oscillating lever.

A separate hydraulic unit is provided to adjust static mean load when compressive minimum loads are desired. It produces a compressive mean load on which the alternating load is superimposed. Load is indicated by two Bourdon-tube manometers measuring maximum differential pressure and minimum differential pressure. The pendulum manometer normally used for static testing is also used to measure maximum pressure in the main or tension cylinder. Valves between cylinders and manometers open towards the manometer and away from the cylinder in the case of maximum load and vice versa. They are operated by the shaft of the eccentric. Hence the pressures in the manometers are virtually static. Load is controlled through electrical contacts on the dials of the differential load manometers. The machine is produced with nominal or static load capacities ranging from 20 to 200 tons. The dynamic load capacity amounts to half the static one. Frequencies range from 200 to 1000 cpm with fixed-frequency selection units and have a lower limit of 100 cpm with continuously variable frequency units. Load accuracy after correction for inertia loads amounts to 3% of load.

Another type of Losenhausen hydraulic fatigue machine, Model UHW, operates with one hydraulic cylinder and uses a spring mechanism for preload adjustment. Its dynamic load capacity measures 6 tons and it has a frequency range of 1000 to 3000 cpm.

In the United States similar machines are produced by the Riehle Company under the trade name Riehle-Los^{56,57,58}. Dynamic capacities range from 5.4 to 136 tons (12,000 - 300,000 lb). When operated by the pulsator frequencies ranging from 125 to 1000 cpm are obtainable. A slow cycle control accessory provides frequencies from 0 to 40 cpm. The maximum strain range amounts to 12.7 to 25.4 (0.5-1.0 in.) using the pulsator and to 152 mm (6 in.) using the slow cycle accessory. Static accuracy is guaranteed to be 0.5% of load. Dynamic accuracy is stated to be 3% of load for the upper 90% of scale capacity, when corrected for inertia of the machine parts according to charts provided by Riehle.

Load programming is possible with both the Losenhausen and the Riehle-Los machines.

B.1.3 G.M.R. Pulsator⁵

This machine, as shown in Figure 10, was developed by the General Motors Corporation. An adjustable crankshaft drives the two actuating pistons (only one is shown in Fig.10). These pistons vary the volumes available to the oil on either side of the main loading piston. Consequently the pressures on either side of the large piston vary. The specimen is connected to the main piston, which in turn applies the variable load to the test piece. By turning one crank pin with respect to the other, the net displacement of the two small pistons, and hence the load amplitude, can be varied. Constant preload is applied before starting the hydraulic system. The loads on the main piston are controlled by leakage and bleed off, governed by a reaction weighing fixture with electronic control equipment. The load capacity is 45 tons (100,000 lb) and the operating speed can reach 2000 cycles per minute. A strain range of 4.3 mm is obtainable.

B.2.1 Universal Elevated-Temperature Testing Machine¹⁴

This machine was developed by S.E. Bramer, K.G. Kahmann Jr., and R. Titus and built by the Marquardt Aircraft Company. It is like an ordinary tensile testing machine where one end of the specimen is attached to a piston in a double-acting hydraulic cylinder. A manually adjusted or automatically programmed voltage, after amplification, operates an electro-mechanical servo transfer valve which controls the flow from a 3000 psi (210 kgf/cm²) hydro-source to the loading cylinder. A load cell in series with the specimen measures its load. The signal is compared with the desired voltage and if an error exists it is corrected automatically by the valve. An extensometer having ceramic knife edges is attached to the specimen and the output from the strain transducer can be used, as with the output from the load transducer, to control strain and strain rate instead of load and loading rate. Direct resistance type of heating is used for high temperature testing. Thermocouples are attached for temperature reading and controlling, again using a feedback system. Hence load (or strain) and temperature can be automatically programmed on this machine. Tests at temperatures up to 2400°F (1320°C) have been conducted. The machine has 23 tons (50,000 lb) load capacity and operates at 0 to 900 cpm.

C. AXIAL FATIGUE MACHINES WITH PNEUMATIC DRIVES

Pneumatically driven axial fatigue machines are not used extensively. However, it should be noted that it is possible to have both high load capacity and low speed with these machines. A brief description of two of these machines follows.

C.1.1 Lehr Pneumatic Fatigue Testing Machine⁴

As shown in Figure 11, dynamic pressure is generated in the cylinder by a reciprocating piston driven by a crank mechanism. Static pre-load is applied when the specimen is mounted in the machine by utilization of preload pressure cylinders. In order to control the load amplitude, the mean air pressure in the spaces between the alternating pressure pistons and the main compressor piston is varied by means of air pressure controllers, so that stroke and volume can be kept constant. The machine has ± 200 tons capacity, operating at 1000 cpm.

C.2.1 ORNL Strain Cycle Apparatus¹⁵

This machine, as shown in Figure 12, was developed and used by the Oak Ridge National Laboratory. It is intended to operate at a very low speed, using strain as the controlled variable instead of stress.

The top shoulder of the specimen is screwed to the lower end of the casing, while the bottom shoulder is screwed to the piston pull-rod which runs through the specimen. By means of controlled gas pressure either on the top or bottom of the piston, the specimen is stressed to produce the desired total strain. Lock nuts, which act as stops, are provided in order to set strain limits. Strain is indicated by a dial gauge. Time per cycle is regulated by a timer (Flexopulse cycle timer) which actuates solenoid valves to apply pressure to either the top or bottom of the piston.

To determine failure, the specimen is internally pressurized at a low pressure which drops when the first complete crack in the specimen occurs. A pressure switch senses the drop and actuates the solenoids to bleed the pressure from the piston and cut off the pressure source, with a timer indicating the life of the specimen.

High temperature tests at temperatures up to 1600°F (872°C) have been conducted on this machine, together with strain cycle speeds of 30 minutes per cycle to 2 minutes or less per cycle. The load capacity is about 2 tons.

D. AXIAL FATIGUE MACHINES, WITH ELECTRO-MAGNETIC DRIVES

Axial fatigue machines with electro-magnetic drives are also widely used in fatigue testing. They operate at relatively high speeds, at the resonance peak of the vibrating system.

D.1.1 Haigh Fatigue Machine^{3,4,5,17}

This machine is shown in Figure 13. One end of the specimen is attached to the frame of the machine and the other end to the armature. The armature oscillates between two magnets energized by two-phase alternating current, one phase being connected to each magnet. Necessary adjustments are made to eliminate unknown inertia forces. First the air gaps around the armature between the two electro-magnets are made equal. Then clamps are moved on the spring until the machine is in resonance with the magnetic excitation, the specimen being unmounted. At this point the inertia loads on the vibrating masses are in dynamic equilibrium with the elastic spring forces. When next the machine is operated with the specimen mounted, the specimen load is directly equal to the magnet force.

The loading capacity of the machine is 6 tons operating at 2000 cpm. P.G. Forrest and H.J. Tapsell designed a special apparatus for 1 to 10 cpm by supplying the coils of the machine with an alternating current of very low frequency¹⁷.

D.1.2 Electro-Magnetic Fatigue Machine¹⁸

This machine, as shown in Figure 14, was designed and built by A. Fransson and used in the Materials Laboratory at Malmslätt, Sweden.

One end of the specimen is attached to the upper pull-rod of the machine and the other end to the armature. Static tensile load is applied by feeding the magnet with direct current, while variable tensile load is applied by alternating current. The specimen together with the upper and lower pull-rod and the armature form a resonance system. Strain gauges are attached to the lower pull-rod to enable checking of load on the specimen. The test is continued until fracture occurs and the machine is automatically stopped. The number of cycles is indicated on a counter.

High frequency induction heating is used to produce cyclic temperature variation. The specimen is in tubular form with thin walls (9 mm o.d. - 8 mm i.d. x 70 mm long) to enable quick heating and cooling. Tests at temperatures up to about 750°C are conducted on this machine.

Tests were performed with 26.5 kgf variable load and up to 395 kgf static load at a frequency of 8300 cpm.

D.2.1 Amsler Vibraphore¹⁹

This machine, as shown in Figure 15, operates on the resonance principle, the number of cycles always coinciding with the natural frequency of the vibrating elements.

One end of the specimen is attached to the bottom of the main moving mass, which is alternately lifted and released by an electro-magnet. The lower end is connected to a second mass through a dynamometer. A vibration pick-up measures the travel of the lower specimen end. Its signal is amplified and fed back to the drive magnet. Thus electro-mechanical resonance is created. The frequency of operation is determined by the stiffnesses of the pre-load spring, the specimen and the dynamometer and by the masses of the main moving mass and the opposing mass. The frequency can be varied by altering the main moving mass when the machine is not running. The dynamometer actuates a mirror. A light beam reflected by the oscillating mirror produces a band of light projected on a scale and an adjustable diaphragm. The light penetrating from the diaphragm in case of overload falls on a photo-electric cell. This produces an a.c. voltage which is amplified and phase shifted. This out-of-phase voltage is fed to the drive magnet and attenuates the drive current and hence the specimen load. Preload is exerted through a power screw. Additional equipment allows maintenance of preload by sensing the mean expansion of the preload spring and operating the drive screw through a reversible electric motor and gear.

The machine can operate at frequencies between 3000 and 18000 cpm and has a nominal capacity of 10 tons for the sum of the static and the dynamic load.

E. THERMO-MECHANICAL AXIAL FATIGUE MACHINES

Thermal fatigue testing is relatively new. Load is applied to a constrained specimen by heating or cooling where the restrained expansion or contraction of the specimen causes alternating stress. Heating can be applied either to the specimen or to parallel columns which hold the platens rigidly on either side of the specimen.

E.1.1 Thermal Expansion Fatigue Machine (Specimen Heated)^{20,21,22}

This machine was originally designed by L.F. Coffin and used by the General Physics Unit, Knolls Atomic Power Laboratory, General Electric Company.

Essentially, the method of testing consists of subjecting a flanged-end thin-walled tubular test specimen to cyclic temperatures. The specimen is clamped rigidly at each end to thick end plates and its thermal expansion and contraction is prevented by two stiff columns attached firmly to the top and bottom plates. In this manner the specimen is subjected to cyclic longitudinal stresses arising from its constrained ends. Consequently the load depends on temperature. Strain gauges are attached to each column. A resistance type of heating is used with the current passing through the specimen itself. Cooling is carried out by means of a gas blast through the specimen. Temperature is measured by a chromel-alumel thermocouple, spot-welded to the specimen. A relay control circuit permits continuous cycling. Before starting the test run thermal deformation of the specimen between high and low temperatures of the cycle is found by cycling the specimen first without, then with, end constraint and subtracting the two quantities.

Set-ups are modified and used to a great extent by the various institutions. At the NASA Lewis Research Center²², a massive block, measuring 7 in. x 7 in. x 3 in., is used to secure the specimen. Again, by means of electric resistance heating, the specimen is subjected to temperature variations which induce thermal stresses in the specimen. The specimen is a solid round piece, the center section being 3/16 in. dia. Cooling is achieved by means of water cooled clamps.

A somewhat modified type of the machine is used by the University of Alabama; a schematic diagram of this machine is shown in Figure 16.

E.2.1 Thermal Expansion Fatigue Machine (Parallel Members Heated)^{20,21}

This machine operates on the same principle as the one described above, except that parallel columns are heated instead of the specimen. Load variation is dependent upon the temperature difference between the specimen and parallel members. A schematic diagram of this machine, which is used by the University of Alabama, is shown in Figure 17.

F. MAGNETO-MECHANICAL FATIGUE MACHINES

Magneto-mechanical drive for fatigue machines is a relatively new idea. A description follows of two such machines, one of which is a reversed bending fatigue machine.

F.1.1 Magneto-Mechanical Bending Fatigue Machine²³

This machine, shown in Figure 18, has been developed by M.R. Achter and G.J. Danek, Jr. and is used in the U.S. Naval Research Laboratory.

The specimen is gripped in an upright position inside a cylindrical vacuum chamber which is enclosed in a split-type furnace. A horseshoe permanent magnet attached to the specimen is excited by two oscillating permanent magnets located outside the vacuum chamber and driven by an eccentric. The machine is driven at the resonant frequency of the specimen.

High temperature tests, up to about 1500°F (815°C), have been conducted with this machine and stresses up to about 27.50 kgf/mm² have been reached with certain specimens. The operating speed ranges from 0 to 420 cpm. In a newer development of the machine immobile a.c. electro-magnets are used instead of the oscillating magnets.

F.2.1 Magnetostriction Fatigue Machine²⁴

This machine, shown in Figure 19, has been developed by E.A. Neppiras and is used in the Mullard Research Laboratories, Salfords, England. It was designed to accelerate the speed of fatigue testing and consists of a resonant magnetostriction transducer coupled to the specimen by means of a transmission line using resonant tapered elements. The transducer is of the laminated dumbbell type and the coupling stubs are each half-wave resonant elements. The specimen, which is approximately resonant at the transducer frequency, is in tapered form. At mid-point its diameter is 3/16 in. and at the ends 3/8 in. It is soldered to the end of the final transformer. The whole assembly is supported by a flange which is attached to a water tank where the magnetostriction transducer is located.

There is no possibility of developing axial pre-stress in this machine. The transducer is driven from a variable frequency oscillator-amplifier; adjustment of the drive power enables the stress level of the specimen to be set at the desired value. The specimen has a central lengthwise 1/16 in. dia. hole for the continuous flow of water for cooling purposes. The machine has about 300 kg load capacity and is operated at very high speeds such as 10⁶ cpm.

APPENDIX II

SURVEY OF EXISTING HEATING FACILITIES

It was indicated earlier that a fatigue machine should be able to perform tests under cyclic heating conditions. This is because in practice temperature changes with the flight condition. The problem, then, is not only to produce high heating rates, but also to provide rapid cooling rates to enable the machine to heat or cool at 300°C to 600°C per minute.

Various methods are available for heating; these are reviewed so that the most suitable one can be selected. It should be noted that only brief descriptions of the facilities and their working principles are given here. Design details are omitted, although for most of the heating facilities diagrams are included. More detailed descriptions can be found in some of the references (e.g. see Ref.59).

Several different sources of energy are used to conduct laboratory tests at elevated temperatures and the available heating methods can be classified as follows:

A. Combustion Furnace Heating

1. Specimen inside the furnace
2. Specimen outside the furnace

B. Electrical Resistance Heating

1. Direct resistance
2. Electrical resistance furnaces
 - (a) gas atmosphere
 - (b) vacuum atmosphere
 - (c) liquid atmosphere
 - (d) fluidized solids atmosphere
3. Incandescent lamps
4. Contact heaters
 - (a) electric blankets
 - (b) sprayed elements

C. Electric Arc Heating

1. Direct arc
2. Indirect arc
 - (a) radiative heat transfer (arc image)
 - (b) convective heat transfer (plasma jet)

D. Electric Induction Heating

1. Direct induction
2. Indirect induction (induction furnaces)

E. Electron Bombardment Heating

F. Solar Furnace Heating

G. Other Means of Achieving High Temperatures.

Relevant information in condensed form is presented in Tables III and IV, taken from Reference 59.

A. COMBUSTION FURNACES^{26, 27, 28, 59}

Combustion furnaces are generally constructed as refractory chambers surrounded by refractory insulation brick or powder and enveloped by thin metal cases. Any combustible gas is mixed with air and burned, reaching temperatures up to 1300°C. By using oxygen or preheating the air, temperatures up to 2400°C can be achieved. Combustion fuels other than gas, such as oil or solids, can also be used.

These furnaces are generally used for melting and heat treating purposes. When applied in testing, the specimen can be placed either inside the furnace or in a separate chamber connected to the furnace by flexible heat resistant tubing.

It is very difficult to achieve short-time temperature cycling with combustion furnaces due to their high thermal inertia. Furthermore, it is difficult to maintain and control the temperature accurately.

Special types of combustion furnaces are pebble beds and fluidized beds.

A pebble bed consists of a vessel where a mass of refractory pebbles rest on a grating. Prior to a test, air premixed with fuel is passed through the bed in a downward direction and burned. The pebbles store the heat emanating from the combustion. When the bed has attained a suitable temperature the fuel flow is shut off and air or any other gas is pumped through in an upward direction and heated by the pebbles. A pebble bed thus serves to produce an intermittent flow of hot gas. This heating method is used mainly in wind tunnel testing when large masses of hot air are required and is less suited for small scale materials testing.

A fluidized bed⁴⁷ consists of a vessel with a porous bottom. It is partially filled with fine-grained powder or flakes. An accurately controlled airflow is passed through the bed in an upward direction. At a certain airflow through the bed the solid particles become airborne and a heavily turbulent mixture of gas and solid particles is created. This leads to a high coefficient of heat transfer between the bed and a specimen immersed in it. The air fed to the bed can be preheated by combustion. It has been found, however, that combustion products tend to block the filter grating supporting the bed⁴⁷ and it appears to be more advantageous to heat the bed electrically by resistance elements surrounding it or by elements immersed in it.

B. ELECTRICAL RESISTANCE HEATING

In this method heat is developed as a result of the passage of electric current through a resistor. In the case of direct resistance heating, the specimen itself is

the resistor. Separate heaters can take the form of wires in furnace windings, incandescent lamps and heater blankets. Other possible heater element shapes are strips, rods, foils, tubes, etc.

With resistance furnaces the specimen is placed either inside the furnace or in a separate chamber connected to the furnace by flexible heat-resistant tubing.

B.1 Direct Electrical Resistance Heating^{14,25,59}

The specimen is connected to an electrical step-down transformer (similar to a welding transformer) delivering a strong alternating current at a low voltage. In this way the specimen can be heated at a rapid rate, i.e. about 100°C per second²⁵, depending upon the size and shape of the specimen.

Direct resistance heating with a transformer is a simple method of energy supply. However, as soon as local lateral contraction or partial fracture occurs, a very undesirable overheating in the necked down-region or cracked area will occur. This will accelerate failure and also spoil the fracture surface for fractographic studies.

Direct current welding sources of power can also be used. These, however, have the added disadvantages of increased arcing at specimen rupture and d.c. pick-up in thermocouple circuits*. Figure 20 shows heating current connectors used in direct resistance heating.

B.2 Electrical Resistance Furnaces^{26,27,28,59}

Electrical resistance furnaces for intermediate temperatures are essentially composed of an insulated casing containing a refractory tube which is tightly wound with wire or strip of suitable dimensions to give a certain total resistance at the desired temperature. Various high temperature furnaces utilize different heating elements such as foil metal tubes or carbon rods.

Electrical resistance furnaces are divided into four main groups according to their atmosphere as follows: (a) gas, (b) vacuum, (c) liquid, (d) fluidized solid. Gas-atmosphere furnaces generally are rather heavily insulated, liquid-atmosphere furnaces are so to a lesser extent. Both have a rather high thermal inertia. Vacuum atmosphere furnaces can do without insulation but need radiation shields instead. In the first two cases both heating and cooling take a relatively long time. In the third case heating progresses quite rapidly but cooling meets difficulties. Forced air convection cooling in (b) is obviously out of the question. Non-reactive gases may sometimes be used. An important advantage of resistance furnaces is the accurate temperature control that can be obtained.

B.2.a Electrical Resistance Furnaces with Air Atmosphere

Generally at temperatures up to 1200°C a nickel chromium alloy resistor is used. Using noble metal wires it is possible to attain temperatures up to 1700°C with these furnaces. A diagram of an electrical resistance furnace used for creep testing is shown in Figure 21. For higher temperatures heating elements such as graphite rods,

*a.c. pick-up is easily detected and filtered out.

molybdenum, tantalum and tungsten foil cylinders must be used in a non-oxidizing atmosphere (vacuum or inert gas).

B.2.b Electrical Resistance Furnaces with Vacuum Atmosphere

Sowman and Andrews of the University of Illinois²⁸ developed a quenching furnace to operate at temperatures up to 2300° in a neutral atmosphere. Argonne National Laboratory modified this furnace to operate at higher temperatures, that is up to about 3200°C. It is a vacuum furnace using a split tungsten heater with tantalum and molybdenum sheet reflectors.

Another vacuum furnace²⁹ was designed and is being manufactured commercially by the Marshall Products Company, Columbus, Ohio. It uses a tantalum heating element surrounded by tantalum and molybdenum radiation shields. This furnace can reach temperatures up to 2200°C and is 11 in. o.d. x 44 in. overall length (Marshall Model 59-TA Vacuum Tensile and Creep Testing Furnace). A furnace of this type is sketched in Figure 22.

B.2.c. Electrical Resistance Heating with Liquid Atmosphere³⁰

A fluid medium electrical resistance heating unit was developed and used by the Convair Pomona Division of the General Dynamics Corporation. Essentially it consists of a reservoir, heating elements (located in the lower portion of the reservoir), a variable speed screw-type pump and a driving motor. A diagram of the unit is shown in Figure 23.

Ordinary petroleum oil was used as fluid in the system. But since the flash point of petroleum is about 650°F (343°C), the temperature range for elevated temperature tests was limited. However, molten salt proved to be satisfactory up to 1000°F (534°C). Needless to say, the operating temperature range of this system is rather low due to the flash or evaporating temperature of the fluids which are used. It is possible, however, to shut off the circulation of hot fluid and pump cold fluid to the system for temperature cycling.

B.2.d Electrical Resistance Heating with Fluidized-Solids Atmosphere

The fluidized bed was already described briefly in Section A. Glenny, Northwood, Shaw and Taylor⁴⁷ have used it to advantage for cooling as well as for heating purposes. The main feature of the fluidized bed is the high coefficient of heat transfer attainable. Also, for this reason, immersing the heater element in the bed permits high bed temperatures, the temperature difference between heater element and bed being less than in the case of a bed surrounded by a heater element. Obviously the bed temperature remains governed by the material of the heaters (e.g. nickel chromium alloy or noble metal). A great disadvantage of the bed is its bulk and the way it intervenes with the specimen loading system. Using it in conjunction with a commercial testing machine is obviously difficult. However, a loading system that could be used is sketched in Figure 12.

B.3 Incandescent Lamps^{31,32,33,35,59}

Radiation heating is the transfer of heat energy by electro-magnetic wave motion between two bodies. Incandescent lamps or rods, producing infra-red rays, are the sources of energy. Very high heat fluxes are possible since the energy emitted is proportional to the fourth power of the temperature. It is possible to attain temperatures up to 1700°C by using incandescent lamps. Heating rates can be high and the desired temperature reached within about 10 to 15 seconds.

Incandescent lamps are commercially produced by various manufacturers in different sizes and shapes. One such lamp, commonly referred to as a pencil lamp, manufactured by the General Electric Company, consists of a coiled tungsten filament wire in a 3/8 in. dia. quartz tube filled with argon gas. A diagram of a radiant heater assembly is shown in Figure 24. It is possible to mount pencil lamps inside a reflective water-cooled vacuum enclosure, thus producing a radiant heated vacuum furnace having the desirable property of low thermal inertia. Incandescent lamp heating could be used effectively for short-time temperature cycling if a proper means of cooling is developed.

B.4 Contact Heaters^{31,35,59}

In this type of heater energy is transmitted by contact conduction. There are two basic forms of contact heaters: (a) electric blanket heaters, and (b) sprayed element heaters. Electric blankets consist of a fine wire grill embedded in a non-conducting matrix to form a blanket. The sprayed element heater consists of a thin coat of non-conducting material and heater element sprayed one on top of the other.

Contact heaters are not suitable for very high temperature tests due to the limitations imposed by the resistance of their non-conducting elements to high temperatures. They are mainly used for temperatures up to about 250°C, although special designs permit higher temperatures.

C. ELECTRIC ARC HEATING

The most common arc is the carbon arc. Rapid surface heating can be obtained by this method and it can operate at temperatures up to 3600°C. Difficulty in maintaining temperature uniformity and control limits its use for laboratory work, but it is widely used in industry for melting purposes where temperature uniformity is not required. Both direct and indirect methods of arc heating are used. In the direct arc method, the arc is formed between an electrode or electrodes and the charge (or specimen). In the indirect arc method, the arc is formed between the electrodes and heats the charge by radiation or forced convection (arc image furnaces and plasma jets respectively).

C.1 Direct Arc Heating

The specimen or charge is struck by the arc and melts. This heating method, therefore, is widely used in welding and materials processing. Obviously it is unsuitable for mechanical testing.

C.2.a Arc-Image Furnace^{26,27,33,59}

An arc image furnace essentially consists of a parabolic or elliptic mirror assembly concentrating the radiation from a carbon or tungsten arc on to a sample. An image of the arc, formed between two electrodes, is formed at the location of the sample by the optical system. The efficiency of the furnace depends on the arrangement of the optical system, radiation from the arc and absorbtivity of the sample. Due to focusing, the heating area is small and concentrated and it is difficult to maintain and control uniformity and magnitude of temperature. However, materials in small quantities can be heated up to 4000°C by this method. For this reason it is mainly used for melting and heat treating purposes. Heat fluxes of 2.5×10^6 Watt/sq.m can be obtained with stable operation for long periods of time.

C.2.b Plasma Jet Heating^{26,34,59}

A stream of water or gas is circulated around an arc which is thus stabilized. Sometimes the arc is further concentrated by a magnetic field in order to give extra-high temperatures. Finally the fluid is forced through the arc-discharge between the concentric electrodes, becomes extremely hot, transforms into plasma and attains a high velocity. One such plasma jet heating unit was designed and developed by Lai, Sloan and Talbot and used at the University of California Institute of Engineering Research (see Fig.25).

A water-cooled carbon cathode and an annular copper anode were used as electrodes in the system. Vacuum was created in the chamber by a pump. Argon gas was introduced to the chamber when proper vacuum pressure was reached. Since argon gas was continuously fed into the chamber, the resulting hot plasma was forced out of the nozzle. Very high temperatures, up to 6000°C, were attained.

Temperature control and uniformity are problems with plasma jets. If, however, a suitable control method is developed, this type of heating could be used for heating purposes in the laboratories. Its application in mechanical testing, however, will not be easy.

D. ELECTRIC-INDUCTION HEATING

An induction heating circuit is basically a transformer where an inductor carrying the alternating current serves as the primary, and the material to be heated is made the secondary by placing it in the alternating magnetic field of the inductor. Heat is generated by means of the eddy currents set up in electrically conductive materials by the rapidly alternating magnetic field. Depth of heat penetration is a function of the frequency of the current, the magnetic permeability and the specific resistance of the test material, i.e.

$$\delta = \frac{1}{2\pi} \left(\frac{\rho}{\mu f} \right)^{\frac{1}{2}}$$

where δ = depth of penetration in cm
 ρ = resistivity in microhm cm
 μ = relative permeability
 f = frequency in kilo-cycles (10^3 Hz).

The temperature distribution on the specimen (susceptor) is heavily influenced by the longitudinal spacing of the coil turns and by the air gap width between coil and specimen (susceptor).

On the basis of the frequency utilized, induction heating equipment can be divided into three classes:

- (a) 500 - 10,000 cps. Equipment: motor generators producing power inputs from 7.5 - 500 kva.
- (b) 10,000 - 450,000 cps. Equipment: spark gap rotary converters, producing 1 - 40 kva.
- (c) 200,000 - 10,000,000 cps. Equipment: electronic valve high-frequency generators producing 0.5 - 100 kva.

Electric induction heating can be obtained both by direct and by indirect (induction furnaces) methods. In direct induction heating, the specimen serves as the secondary while with induction furnaces the specimen is heated indirectly by susceptors. Induction furnaces are generally used for melting and heat treating purposes in industry.

D.1 Direct Induction Heating

In direct induction heating, a high frequency induction generator is connected to the conductor, usually made out of copper, located near the specimen which becomes the secondary of the induction circuit. One such arrangement is shown in Figure 25.

Since the coil is not in contact with the work, induction coils are constructed from hollow copper tubing so that cooling water can be circulated to prevent over heating of the coil. Very high temperatures can be achieved within seconds, the maximum temperature and heating rate being governed by the power input per unit volume and limited by the test material. It should be noted that for efficient heating the skin thickness δ will have to be between 0.2 and 1.0 times the flat specimen thickness or the round specimen radius⁵⁹.

Direct induction heating is suitable for short-time temperature cycling, provided that a proper means of cooling the specimen is developed. Atmosphere control is possible in direct induction heating by surrounding the specimen with a container. It is advantageous to keep the induction coil outside the chamber in order to reduce leakage troubles, in which case, of course, the chamber must be non-conducting, e.g. made of vycor glass.

D.2 Induction Furnaces^{26,27,28}

Induction furnaces are essentially transformers in which a metal cylinder in the furnace is the secondary, heated by eddy currents generated by a primary coil outside the furnace

An induction furnace with a tungsten-ring susceptor is shown in Figure 27. A water-cooled induction coil is mounted outside a vycor-glass chamber. The specimen is

screwed into the bottom and top flanges where bellows permit load application through pull-rods.

Heating by radiation from conducting susceptors in the furnace is advantageous when the test material is not well suited for induction heating and also because design of the work coil is less critical. The advantages of an induction furnace rather than a resistance furnace are the absence of power connectors in the hot zone and the relatively low amperage of the primary, thus lessening the need for heavy bus-bar arrangements.

A variety of induction furnaces are used with different susceptors. One such furnace, developed by the Armour Research Foundation, although not applied in mechanical testing, is of interest due to the fact that it was possible to cool the furnace from temperatures above 2000°C in a few minutes. The specimen is suspended within a cylindrical tantalum heating chamber (susceptor) by a tungsten wire. Vacuum was maintained and temperatures up to 2500°C were attained in the furnace. For rapid cooling an atmosphere inlet was provided which could be used for introducing helium gas. Temperature was determined by an optical pyrometer²⁶.

Another design for a small furnace is noteworthy whereby the furnace tube and the inductor coil are immersed in a water cooling bath²⁶.

For fast short-time temperature cycling the induction furnaces are not too well suited due to added thermal inertia and atmosphere-control requirements.

E. ELECTRON BOMBARDMENT FURNACE^{26, 27}

In the vacuum environment, a stream of electrons emitted from a heated filament can be used as a source of heat. Electrons flow from a hot filament, are accelerated by a high potential, and are focused by charged shields on the anode which is the sample.

Different designs are available according to the purpose for which the furnace is to be used. One such unit, used for zone-refining techniques, consists of a single-turn tungsten wire as the cathode, which is wound around a rod of the material, with molybdenum focusing shields. Temperature can be controlled either by adjusting the filament temperature to control the electron emission, or by adjusting the anode potential to control the electron acceleration. Usually the former method is applied and the anode is kept at a constant potential of several kilovolts.

Electron bombardment furnaces can be used for temperatures up to 2500°C, but are bulky, need a high vacuum and for these reasons are not well adapted for application in mechanical testing.

F. SOLAR FURNACE^{26, 28, 37}

A solar furnace operates on the same principle as an arc-image furnace, except that the sun's rays are focused to produce very high temperatures. One of the problems involved in the operation of this system is the apparatus needed to auto-

matically follow the apparent movement of the sun. It is possible to attain temperatures up to 3000°C, maximum heat flux being about 6×10^6 Watt/sq.m.

It is important to note that solar furnaces can operate only during daylight hours, depending on the state of the weather, while conventional heating units can be utilized at any time. The solar furnace is not well suited for laboratory use in mechanical testing.

G. OTHER MEANS OF ACHIEVING HIGH TEMPERATURES

The following additional heating methods can be mentioned. They are not yet well-suited for materials testing because some of them are restricted to special applications and others are still in the development stage.

Radio-frequency capacitive heating, where non-conductors such as synthetic resins are heated by dielectric losses in a radio-frequency electric field.

Atomic energy release in nuclear reactors.

Shock tube heating, whereby heat emanates from air compression in shock waves.

APPENDIX III

SURVEY OF RAPID HEATING AND COOLING

Various methods are available for rapid heating and cooling. These are reviewed and tests studied so that a suitable technique can be selected.

Heating facilities were discussed earlier and sources providing a rapid rate of heating were indicated. The emphasis here is upon rapid cooling methods. The following breakdown can be made:

- A. Gas Cooling
 - 1. Stagnant gas
 - 2. Forced convection
 - 2.1 in open air
 - 2.2 inside furnace
- B. Liquid Cooling
 - 1. Liquid cooled specimens
 - 2. Liquid cooled clamps
- C. Fluidized Solids Cooling
 - 1. Molten solid
 - 2. Powdered solid.

The three ways in which the transfer of heat may take place are conduction, convection and radiation. In a cooling operation, all three of them may contribute, the extent of each depending upon temperatures, sizes and the materials used. In a rapid heating and cooling cycle, temperature rise is relatively fast at the beginning of the heating cycle. Due to radiation, convection and conduction losses the temperature rise decreases gradually until the desired temperature is reached. During the cooling period the rate of cooling is high at the start, but diminishes as the temperature of the cooling medium is reached (Fig.28). Theoretically the temperature of the cooling medium is reached in infinite time (asymptotically). If minimum temperatures are above room (medium) temperature, heating and cooling cycles will be relatively fast.

The following survey of actual rapid heating and cooling tests is made with emphasis on heating and cooling rates and the cooling methods used:

A. GAS COOLING

The most commonly used gas for cooling is air. Cooling in air can take place either in still air or by forced convection. Cooling in still air takes place at a relatively slow rate because of the low thermal conductivity of air. The heat transfer rate is of the order of 80 Watt/sq.m/^oC (see Ref.47). The rate of cooling is higher with forced convection, depending upon the rate of air flow and air temperature. With an air blast

of 124 m/sec, for instance, a heat transfer rate of 410 Watt/sq.m/⁰C is attainable¹⁷. Low air temperatures can be achieved by utilizing dry ice, for instance. The effectiveness of using other gases depends on their specific heat, thermal conductivity, specific gravity and viscosity. It can be shown that argon and carbon dioxide are less effective than air, that nitrogen is as effective as air and that helium and hydrogen are more effective than air. There are, of course, advantages to using non-reactive gases for cooling purposes. Forced convection cooling is used to a great extent to reduce the cooling time and can effectively be utilized in high temperature tests.

A.1 Induction Heating and Cooling in Still Air¹⁸

The tests were conducted by A. Fransson at the Malmslätt Materials Laboratory.

Machine:	Electromagnetic fatigue machine
Specimen:	Nimonic material (Cr 18, C 0.05, Ni 75, Ti 2.5, Al 1.0, Fe 0.25); heat treated and aged; tubular 9 mm o.d. - 8 mm i.d. x 70 mm long
Heating:	Electric induction, 5×10^5 cps
Cooling:	Still air
Max temp:	750°C
Min temp:	550°C

Maximum temperature was reached in 16 seconds and cooling to minimum temperature in still air took 10 seconds. Hence the heating and cooling frequency was 2.3 cpm, while the cooling rate was about 1200°C/min.

A high cooling rate was attained, even in still air, due to the fact that cooling took place at higher than ambient temperatures. If the desired minimum temperature is in the vicinity of room temperature, cooling in still air may not be sufficiently fast.

Still-air cooling can take place in the open air as indicated above or in the furnace. In the latter case the cooling rate is relatively slow, due to heat storage in the furnace.

A.2.1 Direct Resistance Heating and Forced Convection Air Cooling

(a) The tests were conducted by L.F. Coffin Jr., at the Knolls Atomic Power Laboratory²⁰.

Machine:	Thermal fatigue set-up
Specimen:	Type 347 stainless steel (annealed); tubular 0.540 in. o.d. - 0.500 in. i.d. x 4 in. long, gauge length about 2 in.
Heating:	Direct resistance heating by 2 kva transformer
Cooling:	By air blast on inside surface of specimen; average rate of cooling was about 2400°C/min
Mean temp:	350°C, with temperature ranging from 200 to 500°C
Frequency:	4 cpm

Cooling time was about 7 or 8 seconds.

(b) Similar tests were conducted by Harry Majors Jr., at the University of Alabama³⁸.

Machine: Thermal fatigue set-up
Specimen: Nickel A and Titanium Ti-75 A; size, same as for the Knolls A.P.L. tests above
Heating: Direct resistance heating
Cooling: By air blast on inside surface of specimen in the case of thermal cycling, and through the parallel members in the case of strain cycling

	Nickel	Titanium
Plastic strain range:	0.002	0.001
Coefficient of expansion:	$13.3 \times 10^{-6}/^{\circ}\text{C}$	$8.8 \times 10^{-6}/^{\circ}\text{C}$
Mean temp:	274 ^o C	302 ^o C
Max temp:	424 ^o C	415 ^o C
Min temp:	124 ^o C	189 ^o C
Frequency:	1.67 to 2 cpm	1.67 to 2 cpm
Average cooling rate:	1100 ^o C/min	850 ^o C/min

(c) Thermal shock tests were conducted by Hunter, Thomas and Bobrowsky at the University of Michigan³⁹.

Machine: Thermal shock set-up
Specimen: Special high temperature metals, cermets, stainless steel, Ni-base alloys, Co-base alloys (triangular cross-section)
Heating: Electric resistance with a 1.92 kva transformer
Cooling: Air blast of about Mach 1 velocity through a water-cooled nozzle
Max temp: Ranging from 870 to 1090^oC
Min temp: Not indicated

Tests were run to determine the thermal fatigue life of the abovementioned materials. A testing cycle consisted of 1 minute of heating followed by 5 seconds of cooling. The average cooling rate can be estimated as 10,000^oC/min.

(d) *Combustion heating and forced convection air cooling*

Similar tests were conducted by Lardge at the Materials Laboratory of the Joseph Lucas Gas Turbine Co. Ltd., England⁴⁰.

Machine: Thermal shock set-up
Specimen: Nimonic alloys (annealed), 4 in. square sheets with 0.585 in. dia. hole at the centre
Heating: By gas torch
Cooling: By air blast
Max temp: 1650^oF (900^oC)
Min temp: 120^oF (50^oC)

Temperature was controlled by varying the gas-air supply to each torch as required.

With regard to the cycle, the specimen was heated to the desired temperature, then cooled by air blast. The average cooling rate was about 8400^oC/min, simulating

actual conditions in jet engine flame tubes. Cycle time was 2 minutes, 1 minute heating and 1 minute cooling.

A.2.2 Heating in Furnace and Forced Convection Air Cooling

- (a) Tests were conducted by Shepard, Starr, Wiseman and Dorn at the University of California⁴¹.

Machine: Creep testing apparatus
Specimen: 75 S - T 6 aluminium alloy; flat 0.500 in. wide x 7 1/8 in. long
Heating: Nichrome wound electrical resistance furnace - split type. (In preliminary tests direct resistance heating was added in order to speed up the heating, but later on this was found to be unnecessary)
Cooling: By air blast

Cycle time was 2 hours. The temperature cycle breakdown was as follows: hold at 450°F (233°C) for 1½ hours, then cool to room temperature; hold there and reheat to 450°F in ½ hour. The time required for cooling and holding at room temperature was 10 minutes and the heating time was 20 minutes. The cooling rate was about 30°C per minute. Maximum load was maintained for 1½ hours, then decreased to 0 for ½ hour before reloading. In some of the tests loading was in phase with heating, in others out of phase.

- (b) These tests were conducted by Guarnieri at the Cornell Aeronautical Laboratory⁴².

Machine: Creep testing apparatus
Specimen: Alclad 24 S-T 3 aluminium alloy and FS-1 H magnesium; flat strips 1 in. x 16 in.
Heating: Wire wound electrical resistance furnace, with low mass and low heat capacity. An air space was provided between the lundum inner tube and the outer aluminium shell to act as insulation
Cooling: By blowing cooling air into the furnace

A two hour cycle time was used. Heating was accomplished in 12 minutes to within ±3°C of the desired test temperature. Cooling from 316°C, 232°C and 149°C down to 38°C took 10, 8 and 4 minutes respectively. Cooling down to room temperature (about 16°C) took 16 minutes. The average rate of cooling was about 25°C per minute.

- (c) Further tests were again conducted by Guarnieri⁴³ in order to obtain a faster cooling rate with the same set-up. This time maximum temperature was 1500°F (816°C). Heat was actually applied to the specimen for 1½ hours; it took about 15 minutes to reach the desired temperature.

In the cooling cycle, about 4/5 of the temperature drop occurred in the first 5 minutes. A typical temperature plot for the cooling cycle was as follows:

From 816°C to 177°C in 5 minutes
to 107°C in 10 minutes
to 71°C in 15 minutes
to 46°C in 20 minutes
to 38°C in 25 minutes.

The average cooling rate in the first 5 minutes was about 128°C per minute; however, it decreased rapidly as room temperature was reached. Cycle time was 90 minutes, cool and reheat time being about 15 minutes each.

- (d) The following example is an interesting one where a furnace and a d.c. welder were used for heating. The tests were conducted by Miller at the Thomson Laboratory of the General Electric Company⁴⁴.

Specimen:	High temperature alloys, S 816, M 252; cylindrical shape, as for tensile testing
Heating:	Temperature controlled heating furnace kept at 1500°F (816°C) plus direct resistance heating by d.c. welder
Cooling:	By air blast in furnace
Max temp:	1800°F (982°C)
Min temp:	1500°F (816°C) (operating temperature of the furnace)

Cycling time was 3 minutes, 1 minute for heating and 2 minutes for cooling. The heating rate was 116°C per minute and the cooling rate 58°C per minute on the average.

It can be noticed that heating and cooling rates are rather slow even in furnaces that are specially built with low mass and low heat capacity. Present needs call for something in the order of 300 to 600°C per minute for heating and cooling rates, which are not likely to be attained in furnaces. However, forced convection cooling in the open air permits cooling rates greatly exceeding those required at the present time. Still-air cooling will not suffice when the specimens have appreciable thickness and minimum temperatures are in the vicinity of room temperature.

B. LIQUID COOLING

The most commonly used liquid for cooling is water. In most cases, however, cooling by direct water contact with the specimen is not desirable because of the corrosive effect of water. Furthermore the water will vaporize on first contact and will not condense uniformly. Consequently the cooling rate will not be uniform along the gauge length and unpredictable thermal stresses will occur.

B.1 Water-Cooled Specimens

Thermal shock tests were conducted by Whitman, Hall and Yaker at Lewis Flight Propulsion Laboratory⁴⁵.

Machine:	Thermal shock set-up
Specimen:	Cast alloys such as Vitallium, Stellite 6, etc; concave triangular cross section, $\frac{3}{4}$ in. Δ x 2 in. in length
Heating:	Wire wound electrical resistance furnace
Cooling:	By 45°F (7°C) running water
Max temp:	1750°F (955°C)
Min temp:	Not disclosed

The specimen was heated to 1750°F for one hour, then a narrow edge of the specimen was quenched by 45°F running water, kept at constant temperature through the addition

of dry ice. The cycles were repeated until failure occurred. Special tongs were used to carry the specimen from the furnace to the quenching cup.

B.2 Cooling by Water-Cooled Clamps²⁵

(a) Resistance Heating and Water-Cooled Clamps

These tests were conducted by E.A. Pigan at the Oak Ridge National Laboratory.

Machine: Tensile testing machine, modified for hot ductility tests
Specimen: Inconel and Inconel X; 0.250 in. dia. x 4½ in. in length (solid)
Heating: Direct resistance by 38 kva welding transformer
Max temp: 2500°F (1372°C)
Min temp: 400°F (205°C)

Maximum temperature was reached in 10 seconds. Cooling from 1372°C to 205°C took about 130 seconds.

This method achieves a cooling rate of about 540°C per minute, which is highly satisfactory. It should be noted that the thermal conductivity of the test material used was not exceptionally good. Even faster cooling could therefore be accomplished with other materials.

Water does not come into contact with the specimen, so that there is no danger of corrosion or other adverse effects. A system like this is relatively easy to operate and is not expensive to set up. It is also possible to use water cooled clamps with other types of heating sources, especially with direct induction heating.

(b) Direct Induction Heating and Water-Cooled Clamps

No test has so far come to our notice which has been conducted by direct induction heating with water cooled clamps. There is a good possibility, however, that this combination can be used effectively for rapid heating and cooling cyclic tests. Water cooled clamps were discussed in a previous section as a satisfactory means of cooling the specimen and direct induction heating was indicated to be an effective method of rapid heating.

One experiment using direct induction heating, conducted by Levitt and Martin at Watertown Arsenal Laboratory, is worth mentioning³⁶.

Induction heater: 20 kva 'Scientific Electric' operating at 450 kc/sec
Induction coil: 9 turns of 5/16 in. dia. copper tubing in 3 in. dia. loops and 5½ in. overall length
Specimen: Flat 2 in. gauge length ASTM standard specimens were used and the following results obtained:

Specimen thickness	Heating rate °C/min
.078 in. (1.98 mm)	2400
.045 in. (1.14 mm)	1320
.031 in. (0.79 mm)	1140

All of these are above the recommended maximum heating rate of 600°C/min.

C. FLUIDIZED SOLIDS COOLING

The nature of a fluidized solid in this context can be either of the following:

1. A molten metal
2. A powder of which each individual grain is supported by an accurately controlled gas flow.

C.1 Thermal Load Cycling with Liquid Sodium

Thermal cycling tests were conducted on Beryllium by Kelley, Platus and Tallackson at the Oak Ridge National Laboratory⁴⁶, using liquid sodium. A thick walled perforated beryllium cylinder was surrounded by an inconel housing with openings for liquid flow. The inner and outer cylindrical surfaces of the specimen were held at the desired temperatures by passing through liquid sodium of controlled temperature. The following results were obtained:

Max temp:	1250°F (677°C)
Min temp:	900°F (482°C)

Cycle time was 1 hour; about 7.5 minutes were required for heating and 7.5 minutes for cooling. The cooling rate was about 26°C per minute.

C.2 Heating and Cooling in Fluidized Beds⁴⁷

The test equipment was developed by Glenny, Northwood, Shaw and Taylor and is used at the National Gas Turbine Establishment, Farnborough, England.

(a) Heating in Furnace and Cooling by Cold Fluidized Bed

An induction furnace was used for heating. Cooling was done by immersion of the specimen into the cold fluidized bed. This consists of a container holding a bed of powder supported on a permeable plate. A gas stream was forced through the plate. Thereupon the powder became airborne and a heavily turbulent mixture of gas and powder resulted. The overall density of the mixture and the heat transfer coefficient depend on the gas flow rate. Generally silicon carbide powder is used. A disc shaped tapered specimen was used, with a hole at the centre for holding purposes.

Cooling from a temperature of 820°C down to 220°C took 15 seconds (rate of 2400°C/min). The average heat transfer rate was reported as 820 Watt/m²/°C. Heating in the furnace took 8 minutes and cooling in the fluidized bed 2 minutes. Cycle time was 10 minutes.

(b) Heating in Fluidized Bed and Cooling in Air or Air Blast

Heating is also possible in the fluidized bed when it is either chemically or electrically heated. Specimens were similar to the one mentioned above. Cycle time was 8 minutes. The period of heating in the fluidized bed was 75 seconds, followed by cooling in still air or by forced air convection.

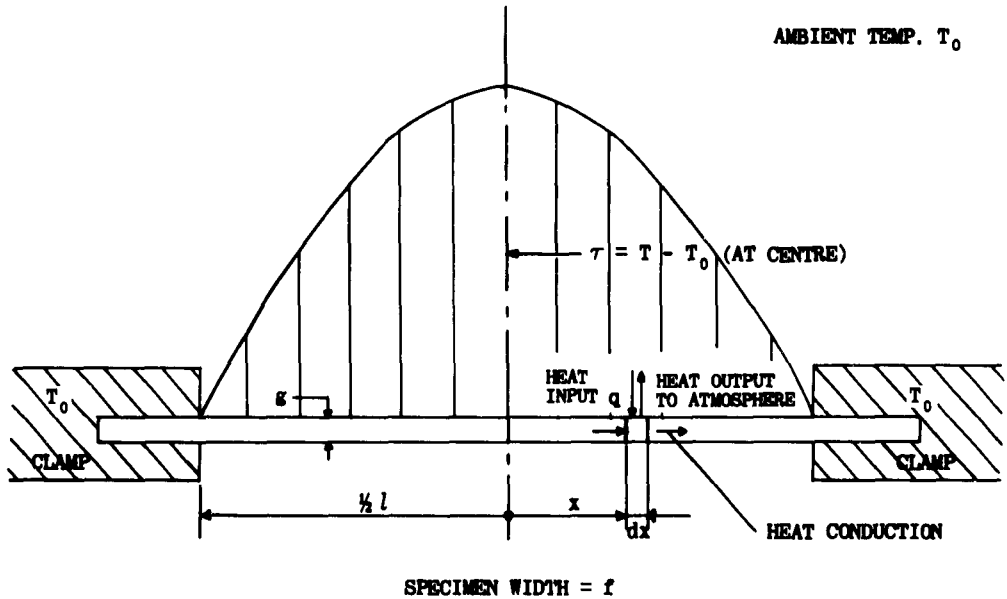
(c) Alternate Heating and Cooling by Fluidized Beds

Two fluidized beds were mounted side by side. One was electrically heated, the other was operated at room temperature. The specimen was automatically transferred from one bed to another. An electronic timer controlled the immersion periods, ranging from 25 sec to 48 min. Transfer time was negligible for heat transfer effects, being as little as 1.5 sec.

It would be difficult to use fluidized beds for cyclic heating high-temperature tests, because of the interference between the loading system and the fluidized bed.

APPENDIX IV COMPARISON OF COOLING METHODS

In many rapid-heating tests the temperature distribution can be approximated by a cosine function.



The heat balance equation for an element of length dx of the specimen can be written down as

$$q \cdot 2(f + g)dx = c\rho \cdot fgdx \cdot \frac{dT}{dt} + h \cdot 2(f + g)dx \cdot (T - T_0) +$$

$$- k \cdot fgdx \cdot \frac{d^2T}{dx^2} + \epsilon\sigma \cdot 2(f + g)dx \cdot (T^4 - T_0^4).$$

Introducing $r = \frac{fg}{2(f + g)}$,

$$q = r c \rho \frac{dT}{dt} + h(T - T_0) - rk \frac{d^2T}{dx^2} + \epsilon\sigma(T^4 - T_0^4).$$

In the case of cooling $q = 0$.

1. CONVECTIVE HEAT TRANSFER ONLY

$$rc\rho \frac{dT}{dt} = -h(T - T_0), \text{ with } T - T_0 = \tau \cos \frac{\pi x}{l}$$

$$\frac{d\tau}{dt} = -\frac{h}{rc\rho} \tau.$$

$$\tau = \tau_{in} \exp\left\{-\frac{h}{rc\rho} t\right\}, \text{ with } \tau_{in} = \text{initial temperature.}$$

The condition $\tau = 0$ is reached asymptotically. The time t^* after which $\tau = \tau_{in}/e^2$ is equal to

$$t^* = \frac{2rc\rho}{h}.$$

t^* thus presents the time after which τ has dropped to $0.14\tau_{in}$, or 86% of the temperature drop has occurred.

2. CONDUCTIVE HEAT TRANSFER ONLY

$$rc\rho \frac{dT}{dt} = rk \frac{d^2T}{dx^2}.$$

In many rapid-heating tests the temperature distribution can be approximated by a cosine function i.e.

$$T - T_0 = \tau \cos \frac{\pi x}{l}.$$

Hence

$$c\rho \frac{d\tau}{dt} = -k \frac{\pi^2}{l^2} \tau$$

$$\frac{d\tau}{dt} = -\frac{k}{c\rho} \frac{\pi^2}{l^2} \tau$$

$$\tau = \tau_{in} \exp\left\{-\frac{k\pi^2}{c\rho l^2} t\right\}$$

$$t^* = \frac{2c\rho l^2}{k\pi^2}.$$

3. CONVECTIVE HEAT TRANSFER + CONDUCTIVE HEAT TRANSFER ONLY

$$rc\rho \frac{dT}{dt} = -h(T - T_0) + rk \frac{d^2T}{dx^2}.$$

$$\text{With } T - T_0 = \tau \cos \frac{\pi x}{l},$$

$$rc\rho \frac{d\tau}{dt} = -h\tau - rk \frac{\pi^2}{l^2} \tau$$

$$\frac{d\tau}{dt} = - \left\{ \frac{h + rk\pi^2/l^2}{rc\rho} \right\} \tau$$

$$\tau = \tau_{in} \exp \left\{ - \frac{h + rk\pi^2/l^2}{rc\rho} t \right\}$$

$$t^* = \frac{2rc\rho}{h + rk\pi^2/l^2}.$$

4. RADIATIVE HEAT TRANSFER ONLY

$$rc\rho \frac{dT}{dt} = -\epsilon\sigma(T^4 - T_0^4)$$

$$\frac{dT}{T^4 - T_0^4} = - \frac{\epsilon\sigma}{rc\rho} dt.$$

$$\text{Introducing } \theta = \frac{T}{T_0},$$

$$\frac{d\theta}{\theta^4 - 1} = - \frac{\epsilon\sigma}{rc\rho} T_0^3 dt$$

$$-\frac{1}{2} \frac{d\theta}{\theta^2 + 1} - \frac{1}{4} \frac{d\theta}{\theta + 1} + \frac{1}{4} \frac{d\theta}{\theta - 1} = - \frac{\epsilon\sigma}{rc\rho} T_0^3 dt$$

$$-\frac{1}{2} \arctan \theta + \frac{1}{4} \log_e(\theta + 1) - \frac{1}{4} \log_e(\theta - 1) = \frac{\epsilon\sigma}{rc\rho} T_0^3 (t + t_0).$$

$$\text{At } t = 0 \quad \theta = \theta_{in}$$

$$\frac{1}{2} \arctan \theta_{in} + \frac{1}{4} \log_e (\theta_{in} + 1) - \frac{1}{4} \log_e (\theta_{in} - 1) = \frac{\epsilon \sigma}{rc\rho} T_0^3 t_0.$$

Hence:

$$2(\arctan \theta - \arctan \theta_{in}) + \log_e \frac{\theta + 1}{\theta_{in} + 1} - \log_e \frac{\theta - 1}{\theta_{in} - 1} = 4 \frac{\epsilon \sigma}{rc\rho} T_0^3 t.$$

The time t^* needed for $T - T_0$ to drop from $T_{in} - T_0$ to $(T_{in} - T_0)/e^2$ can be calculated as the time needed for θ to drop from θ_{in} to $(\theta_{in} - 1 + e^2)/e^2$ viz.,

$$2 \left[1 - \arctan \theta_{in} + \arctan \frac{e^2 + \theta_{in} - 1}{e^2} \right] + \log_e \frac{2e^2 + \theta_{in} - 1}{e^2(\theta_{in} + 1)} = 4 \frac{\epsilon \sigma}{rc\rho} T_0^3 t^*.$$

5. NUMERICAL CALCULATIONS FOR A PRACTICAL CASE

The case selected involves a specimen made of Nimonic 80A, a high-temperature nickel alloy, with properties as listed in Table V.

With regard to convective cooling, four different media are considered (Table V).

As typical cooling times, the times t^* required for a temperature drop from T_{in} (i.e. 900°C) down to $e^{-2} \times (T_{in} - T_0) + T_0$ (i.e. 140°C) are calculated for the following cases:

- (a) cooling in still air only
- (b) cooling in an airblast of 124 m/sec only
- (c) cooling in fluidized bed only
- (d) cooling in still water only
- (e) conductive cooling only (representative of liquid cooled clamps)
- (f) the combination of liquid cooled clamps and still air
- (g) the combination of liquid cooled clamps and forced convection
- (h) cooling by radiation only.

The results are presented in Table VI. Average cooling rates can be calculated by dividing the temperature drop by the cooling time t^* . It should be noted that for convective and conductive cooling the times t^* are virtually independent of the initial temperature difference (Sections 1 and 2). The average cooling rates therefore will be nearly proportional to the initial temperature difference.

Considering the requirement of a cooling rate between 300 and 600°C/min (5-10°C/sec) it can be concluded that on the average the combination of conductive cooling and still air cooling will be the most suitable cooling method. Other methods are either too slow or too fast. It should be noted that with conductive cooling, thermal gradients on the specimen will mostly be longitudinal and with other methods lateral. Consequently thermal stresses will be relatively low with conductive cooling.

The combination of water-cooled clamps and still air cooling, therefore, is recommended in general. It may happen, however, that the cooling rate is too fast with

thin specimens, high initial temperatures and materials like Al, Mg and W which have high thermal conductivities, and too slow in the case of thick specimens and low initial temperatures. In the first case, then, the specimen should be (partially) insulated from the clamps and in the second case forced convection should be added. It may be necessary to test the material in vacuum. Apparently, conductive cooling will be the only possible method, radiation cooling being rather ineffective at temperatures below 1000°C. In this case thought should be given to flushing the vacuum chamber with inert gas. When the specimen atmosphere has to be inert conditions will not differ appreciably from still air conditions if the inert gas is circulated at a relatively low flow rate.

A P P E N D I X V

T A B L E S

TABLE I

Values of $\frac{1}{6}\sigma_u$ and $\frac{1}{2}(\sigma_{0.2} + \sigma_u)$ for Various Materials

Material	$\sigma_{0.2}$ (kgf/mm ²)	σ_u (kgf/mm ²)	$\frac{\sigma_u}{6}$ (kgf/mm ²)	$\frac{\sigma_{0.2} + \sigma_u}{2}$ (kgf/mm ²)	Loads at RT and					$\frac{\sigma_{0.2} + \sigma_u}{2} \cdot \frac{A}{6}$
					t=1mm A=12.7mm ²	t=3.2mm A=40.64mm ²	t=6.4mm A=81.28mm ²	t=12.7mm A=126.68mm ²	t=12.7mm A=161.29mm ²	
Mg-alloy Hk 31A-T6	11	22	3.7	16	203 47	650 150	1299 301	2027 469	2558 597	
Al-alloy 2024-T3	31	47	7.8	39	495 99	1584 317	3168 634	4940 988	6286 1257	
Ti-alloy Ti-6Al-4V	99	106	17.6	102	1295 224	4144 717	8288 1434	12921 2230	16446 2845	
Alloy steel Vascojet 1000	150	183	30.5	166	2108 387	6746 1238	13491 2477	21029 3864	26772 4915	
S.A.P.H. steel PH15-7Mo, RH950	154	166	27.6	160	2032 350	6502 1120	13005 2240	20269 3496	25806 4445	
Ni-alloy Nimonic 90	79	126	21.0	102	1295 267	4144 854	8288 1709	12921 2660	16446 3391	
Co-alloy S-816	47	98	16.3	72	914 207	2925 662	5850 1325	9121 2065	11608 2629	
Mo-alloy Mo-0.5Ti	69	76	12.6	72	914 160	2925 512	5850 1024	9121 1596	11608 2032	
Niobium (0.1% O)	42	56	9.3	49	622 118	1990 378	3981 755	6207 1178	7899 1499	
Tantalum	40	50	8.3	45	572 105	1830 336	3661 672	5701 1051	7264 1334	
Tungsten (6.3mm ϕ)	45	50	8.3	48	610 105	1952 336	3904 672	6081 1051	7747 1334	
Graphite	?	3-5	0.6	⁴ (estimated)	8	26	51	76	507	102

	age attainable heat transfer rate (watts/cm ² °C)	Average attainable temperature rate (°C/sec)
Chemical heat sources		
(1) Combustion	not applicable	0.1
(2) Partially	0.10	120
(3) Pebble bed	0.05	50
(4) Fluidized bed	0.10	100
Nuclear heat sources		
(1) Solar furnace	not applicable	1200
(2) Nuclear reactor	?	?
Electrical heat sources		
(1) Direct resistance	not applicable	400
(2) Resistance	not applicable	0.1
(3) Contact resistance	0.05	10
(4) Resistance	0.10	100
(5) Direct high frequency	not applicable	400
(6) Indirect high frequency	not applicable	200
(7) High frequency	not applicable	200
(8) Incandescence	not applicable	200
(9) Electrical	not applicable	500
(10) Plasma jet	0.05	300
(11) Electron beam	not applicable	1500

TABLE I

Summary of Advantages and Disadvantages

	Attainable temperature level	Attainable heating rate	Attainable cooling rate	Ease of temperature measurement	Control of specimen temperature distribution	Control of specimen temperature level	Control of specimen
Chemical heat sources							
(1) Combustion furnaces	high	low	low	normal	difficult	difficult	limited
(2) Partially confined or unconfined flames	high	high	high	normal	difficult	difficult	unfeasible
(3) Pebble bed heaters	high	high	high	normal	difficult	difficult	limited
(4) Fluidized beds	high	high	high	normal	difficult	difficult	limited
Nuclear heat sources							
(1) Solar furnaces	very high	very high	high	difficult	difficult	difficult	difficult
(2) Nuclear reactors	high	-	-	-	Merits in present	present	applicable
Electrical heat sources							
(1) Direct resistance heating	very high	very high	high	difficult	difficult	easy	feasible
(2) Resistance furnaces	high	low	low	normal	easy	easy	easy
(3) Contact resistance heaters	low	low	low	normal	difficult	easy	difficult
(4) Resistance heated fluidized beds	high	high	high	normal	difficult	easy	limited
(5) Direct h.f. induction heating	very high	very high	high	difficult	feasible	difficult	easy
(6) Indirect h.f. induction heating	high	high	low	normal	feasible	difficult	easy
(7) High frequency capacitive heating	high	high	low	difficult	difficult	difficult	feasible
(8) Incandescent rod and lamp heating	high	high	high	normal	easy	easy	feasible
(9) Electrical heat source imaging furnaces	very high	very high	high	difficult	difficult	easy	feasible
(10) Plasma jets	very high	very high	high	difficult	difficult	difficult	limited
(11) Electron bombardment furnaces	high	very high	low	difficult	difficult	easy	unfeasible



FILE IV

Disadvantages of Heating Methods

Temperature level	Control of specimen atmosphere	Disturbance by electro-magnetic fields	Applicability to various materials	Adaptability to commercial testing machines	Accessibility of specimen	Bulk of equipment in direct vicinity of specimen	Preferential specimen dimensions	Commercial availability of equipment	Cost of equipment
cult cult cult cult	limited unfeasible limited limited	absent absent absent absent	unrestricted unrestricted unrestricted unrestricted	difficult difficult difficult difficult	poor good poor poor	great small great great	small small large small	limited good poor poor	low low high moderate
cult ent	difficult application	absent still	unrestricted largely unknown	difficult -	poor -	great -	small -	limited -	high -
cult cult cult cult cult cult	feasible easy difficult limited easy easy feasible feasible feasible limited unfeasible	present preventable negligible preventable present present present negligible negligible present present	conductors only unrestricted unrestricted unrestricted conductors only unrestricted non-conductors only unrestricted unrestricted unrestricted conductors only	easy easy easy difficult easy easy easy easy difficult difficult difficult	good poor poor poor good poor good good poor poor poor	small great small great small small small small great great great	small small small small small small small large small small small	good good good poor good good good good poor limited poor	low moderate low moderate high high high low high high high



T A B L

Suggested Machine Appl

<i>Type of test</i>	<i>Suggested machine:</i>
A. Slow simulation of actual load and temperature history	<ol style="list-style-type: none"> 1. Baldwin-Emery SR-4, Model FGT, with added control equip 2. Instron Model TT-CM-L with added control equipment 3. Simple hydraulic loading device with sophisticated cont 4. Powerful electrodynamic loading device with sophisticat
B. Low frequency load cycling at steady temperatures	<ol style="list-style-type: none"> 1, 2, 3, 4 as under A 5. Baldwin-Sonntag Model IV-4V with P-10R programmer 6. Schenck Model PHQO 7. Riehle-Los RL 30/40 DA hydraulic pulsator 8. Dynamic creep testing machine (Pao and Marin) of increa 9. 15,000 lb Krouse machine with added slow drive 10. Haigh fatigue machine with added slow drive and control
C. Low frequency load cycling at cyclic temperatures	<ol style="list-style-type: none"> 1, 2, 3, 4 as under A 5, 6, 7, 8 as under B
D. High frequency load cycling at steady temperatures	<ol style="list-style-type: none"> 1. Baldwin-Sonntag Model IV-4V 2. Schenck Model PHQO 3. Riehle-Los RL 30/40 DA hydraulic pulsator 4. Haigh fatigue machine with added control equipment 5. 15,000 lb Krouse machine of increased frequency 6. Dynamic creep testing machine (Pao and Marin) of increas 7. Powerful electrodynamic loading device with sophisticate
E. High frequency load cycling at cyclic temperatures	<ol style="list-style-type: none"> 1, 2, 3 as under D 4. Dynamic creep testing machine (Pao and Marin) of increas 5. Powerful electrodynamic loading device with sophisticate



TABLE VII

Applications and Developments

<i>machines</i>	<i>Suggested heating methods</i>	<i>Suggested cooling methods</i>
l equipment nt ed control equipment (Bramer, Kahmann and Titus) isticated control equipment	1. High frequency induction 2. Radiant heating 3. Direct resistance	1. Water-cooled clamps 2. Forced convection
r increased capacity and with added slow drive control equipment	1. Resistance furnace	1. None
nt increased capacity and frequency isticated control equipment	1. High frequency induction 2. Radiant heating 3. Direct resistance 1. Resistance furnace	1. Water-cooled clamps 2. Forced convection 1. None
increased capacity and frequency isticated control equipment	1. High frequency induction 2. Radiant heating 3. Direct resistance	1. Water-cooled clamps 2. Forced convection

(Continued).....

TABLE VII

Suggested Machine Applicati

Type of test	Suggested machines
(a) Slow simulation of actual strain and temperature history	1. Baldwin-Emery SR-4, Model FGT, with extensometer and add: 2. Instron Model TT-CM-L with extensometer and added contro: 3. Simple hydraulic loading device with extensometer and soj (Bramer, Kahmann and Titus) 4. Powerful electrodynamic loading device with extensometer
(b) Low frequency strain cycling at steady temperatures	1, 2, 3, 4 as under (a) 5. 15,000 lb Krouse fatigue machine with added slow drive ar 6. Baldwin-Sonntag Model IV-4V with P-10R programmer and sui 7. Schenck model PHQO with suitable extensometer 8. Riehle-Los RL 30/40 DA with strain limiting device or ext 9. Dynamic creep machine (Pao and Marin) of increased capaci strain limiter
(c) Low frequency strain cycling at cyclic temperatures	1, 2, 3, 4 as under (a)
(d) High frequency strain cycling at steady temperatures	1. 15,000 lb Krouse fatigue machine with increased frequency 2. Baldwin-Sonntag Model IV-4V with suitable extensometer and eccentric weight 3. Schenck model PHQO with suitable extensometer 4. Riehle-Los RL 30/40 DA with strain limiting device or ext 5. Dynamic creep machine (Pao and Marin) of increased capaci limiting device 6. Powerful electrodynamic loading device with extensometer s
(e) High frequency strain cycling at cyclic temperatures	1. Powerful electrodynamic loading device with extensometer s

Note: In cyclic temperature tests it is sugge
 subjected to the same temperature histo
 high temperature extensometers could be
 signal from the dummy specimen could be
 active specimen and the resulting signa
 and could be applied for strain control.



TABLE VII (Contd.)

Machine Applications and Developments

<i>Tested machines</i>	<i>Suggested heating method</i>	<i>Suggested cooling method</i>
<p>ensometer and added control equipment</p> <p>and added control equipment</p> <p>tensometer and sophisticated control equipment</p> <p>with extensometer and sophisticated control equipment</p> <p>ided slow drive and strain limiter</p> <p>programmer and suitable extensometer</p> <p>meter</p> <p>ing device or extensometer</p> <p>f increased capacity, with added slow drive and</p>	<p>1. High frequency induction</p> <p>2. Radiant heating</p> <p>3. Direct resistance</p> <p>1. Resistance furnace</p> <p>1. High frequency induction</p> <p>2. Radiant heating</p> <p>3. Direct resistance</p> <p>1. Resistance furnace</p>	<p>1. Water-cooled clamps</p> <p>2. Forced convection</p> <p>1. None</p> <p>1. Water-cooled clamps</p> <p>2. Forced convection</p> <p>1. None</p> <p>1. Water-cooled clamps</p> <p>2. Forced convection</p>

tests it is suggested that a dummy specimen be used, temperature history as the active specimen. Reliable nosometers could be mounted on both specimens. The specimen could be subtracted from the signal from the he resulting signal would represent mechanical strain for strain control.



TABLE V

Comparison of Cooling Methods, Basic Data

Specimen

material	Nimonic 80A
density	$\rho = 8.2 \text{ gram/cm}^3$
specific heat	$c = 0.536 \text{ joule/gram } ^\circ\text{C (average 20-900 } ^\circ\text{C)}$
thermal conductivity	$k = 0.201 \text{ watt/cm } ^\circ\text{C (average 20-900 } ^\circ\text{C)}$
emissivity	$\epsilon = 0.48 \text{ (oxidized at 600 } ^\circ\text{C)}$
width	$f = 1.27 \text{ cm (}\frac{1}{2} \text{ in.)}$
length	$l = 10.16 \text{ cm (4 in.)}$
thickness	$g_1 = 0.1 \text{ cm; } g_2 = 0.32 \text{ cm (}\frac{1}{8} \text{ in.); } g_3 = 0.64 \text{ cm (}\frac{1}{4} \text{ in.)}$

$$\text{ratio } \frac{fg}{2(f+g)} \quad r_1 = 0.0464 \text{ cm; } r_2 = 0.1278 \text{ cm; } r_3 = 0.2128 \text{ cm}$$

$$\text{quantity } r\rho c = 0.204 \text{ joule/cm}^2 \text{ } ^\circ\text{K; } = 0.562 \text{ joule/cm}^2 \text{ } ^\circ\text{K; } = 0.935 \text{ joule/cm}^2 \text{ } ^\circ\text{K}$$

$$\text{quantity } rk \frac{\pi^2}{l^2} = 0.000891 \text{ watt/cm}^2 \text{ } ^\circ\text{K; } = 0.002454 \text{ watt/cm}^2 \text{ } ^\circ\text{K; } = 0.004086 \text{ watt/cm}^2 \text{ } ^\circ\text{K}$$

Convective heat transfer coefficient

still air	$h_1 = 0.008 \text{ watt/cm}^2 \text{ } ^\circ\text{K}$
air blast 124 m/sec	$h_2 = 0.041 \text{ "}$
fluidized bed	$h_3 = 0.082 \text{ "}$
still water 15 °C	$h_4 = 0.123 \text{ " (average)}$

Radiative heat transfer data

Stefan-Boltzmann constant	$\sigma = 5.667 \times 10^{-12} \text{ watt/cm}^2 \text{ } ^\circ\text{K}^4$
initial temperature	$T_{in} = 1173 \text{ } ^\circ\text{K (900} ^\circ\text{C)}$
ambient temperature	$T_0 = 293 \text{ } ^\circ\text{K (20} ^\circ\text{C)}$
temperature difference	$\tau = 880 \text{ } ^\circ\text{K (880} ^\circ\text{C)}$
relative initial temp.	$\theta_{in} = 4.003$
quantity $4\epsilon\sigma T_0^3$	$= 273.688 \times 10^{-6} \text{ watt/cm}^2 \text{ } ^\circ\text{K}$

TABLE VI

Cooling Times, t^* after which $T - T_0 = (T_{in} - T_0)/e^2$ for
 $T_{in} = 900^\circ\text{C}$, $T_0 = 20^\circ\text{C}$

Cooling method (Specimen thickness: 0.1 cm; 0.32 cm; 0.64 cm)

Convective heat transfer only

still air	51 sec; 140 sec; 234 sec
air blast, 124 m/sec	10 sec; 27 sec; 46 sec
fluidized bed	5 sec; 14 sec; 23 sec
still water, 15°C	3 sec; 9 sec; 15 sec

Conductive heat transfer only 457 sec; 457 sec; 457 sec

Conductive + convective heat transfer only

still air	46 sec; 108 sec; 155 sec
air blast, 124 m/sec	10 sec; 26 sec; 42 sec

Radiative heat transfer only 387 sec; 1068sec; 1775sec

Note: Cooling times, t^* , for conductive and convective heat transfer are virtually independent of initial temperature difference, whereas those for radiative heat transfer strongly depend on initial temperature difference.

A P P E N D I X V I

FIGURES

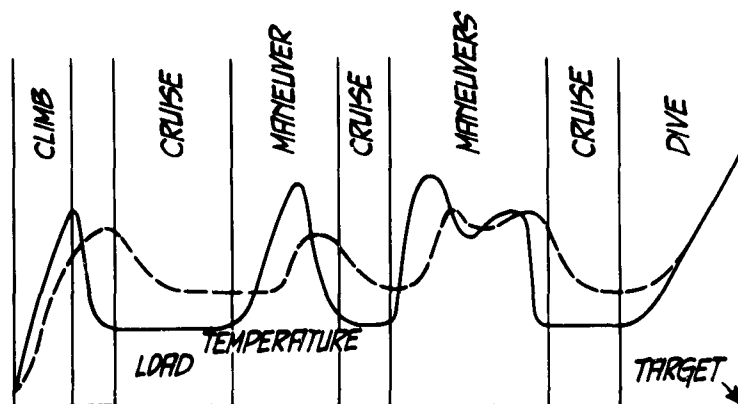


Fig.1 Hypothetical load and temperature history of a missile power plant component

Fig. 2 Types of cyclic heating tests

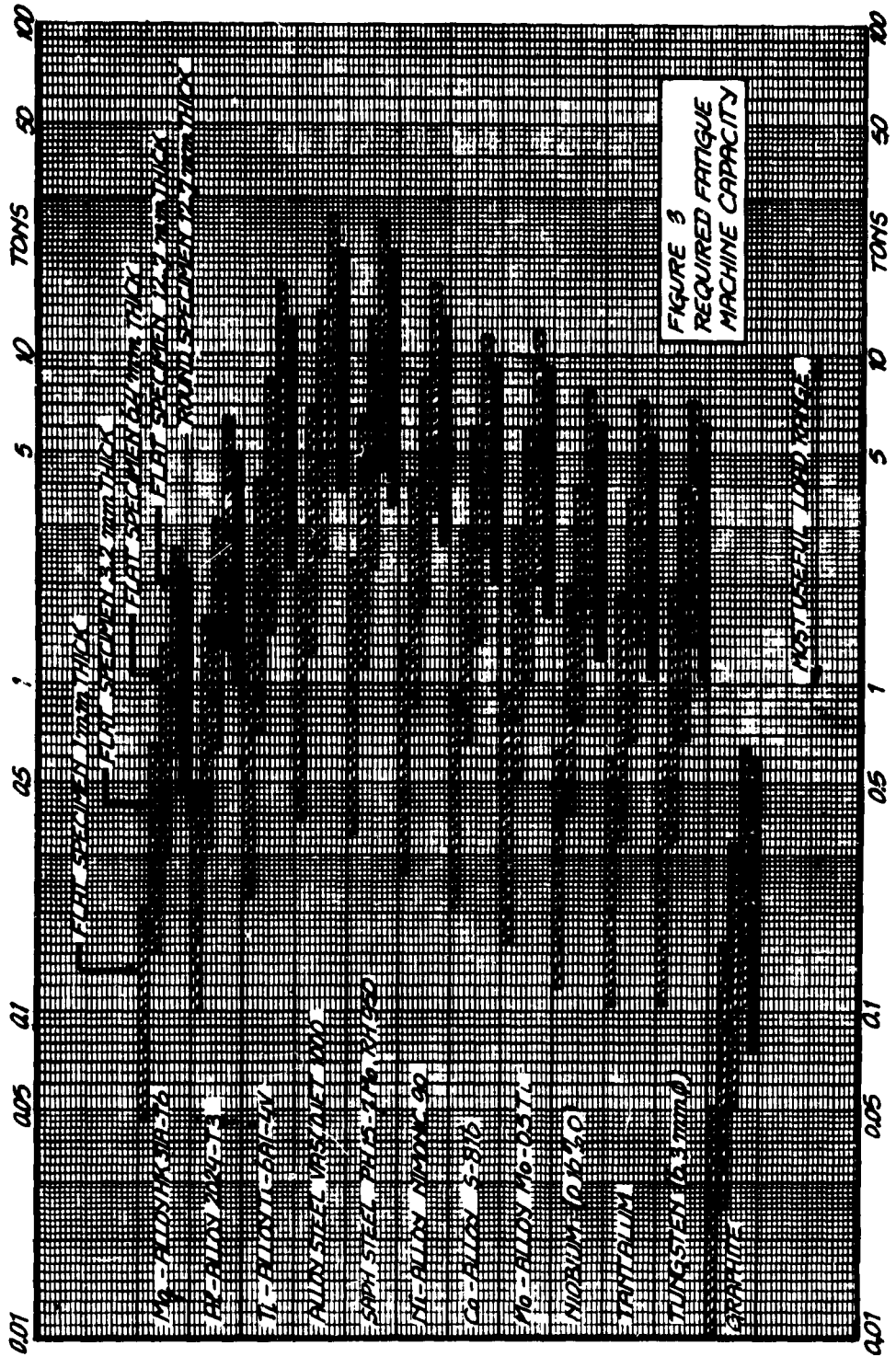


Fig. 3 Required fatigue machine capacity

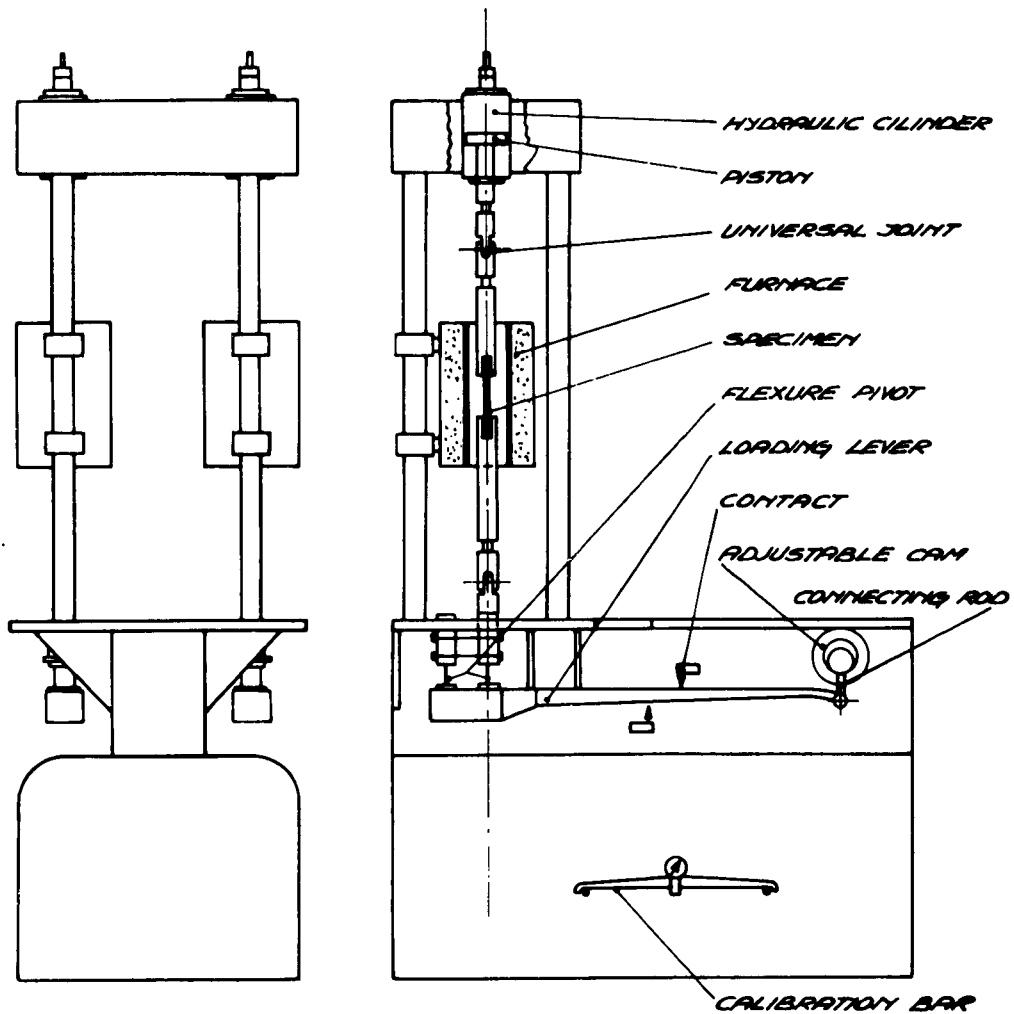


Fig.4 Schematic diagram of Krouse fatigue machine equipped with furnace

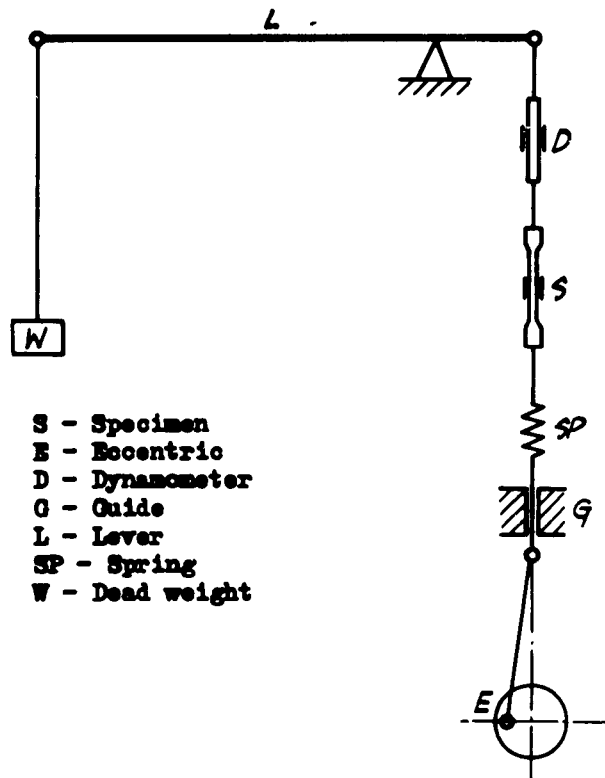


Fig.5 Schematic diagram of dynamic creep testing machine

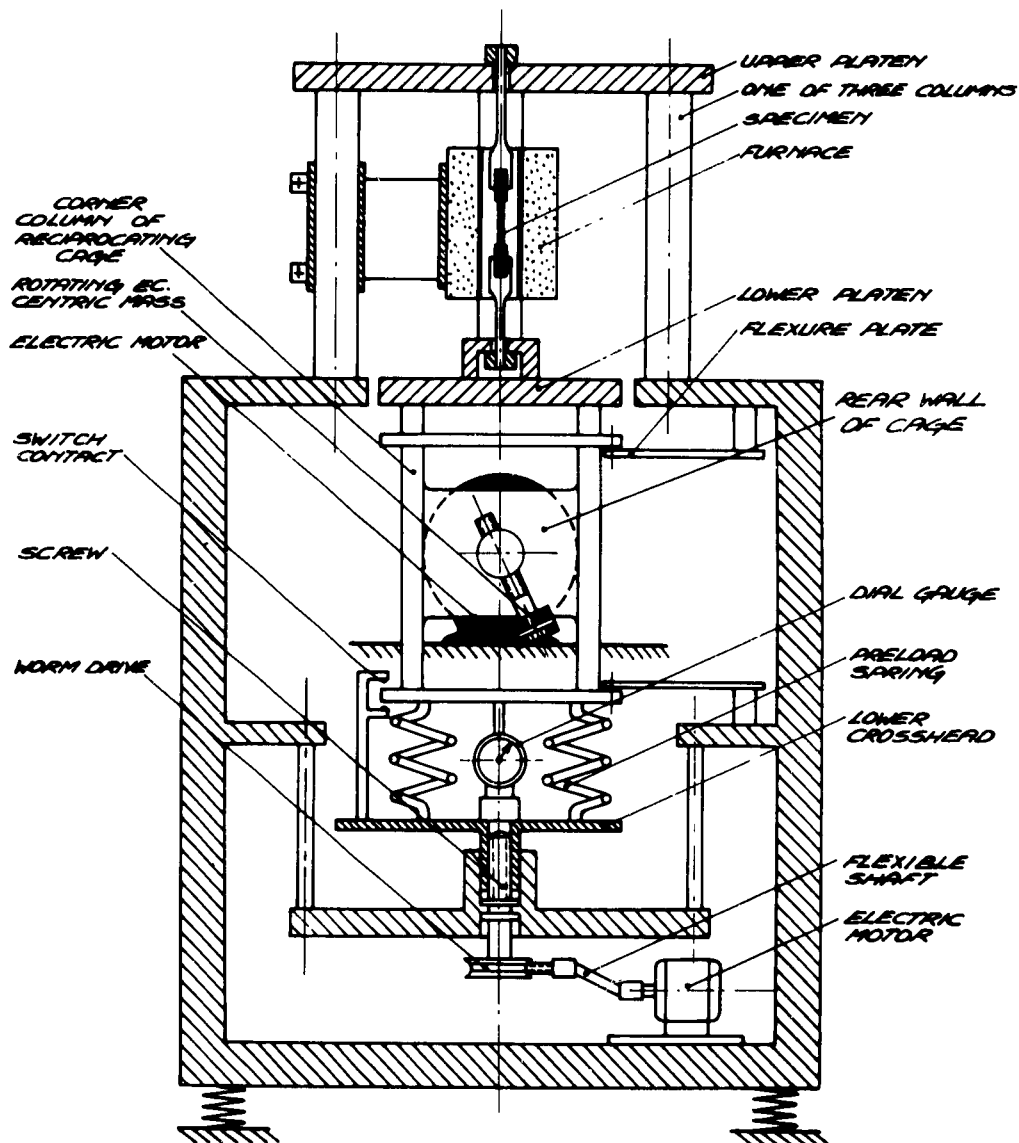


Fig.6 Schematic diagram of Sonntag fatigue machine, equipped with furnace

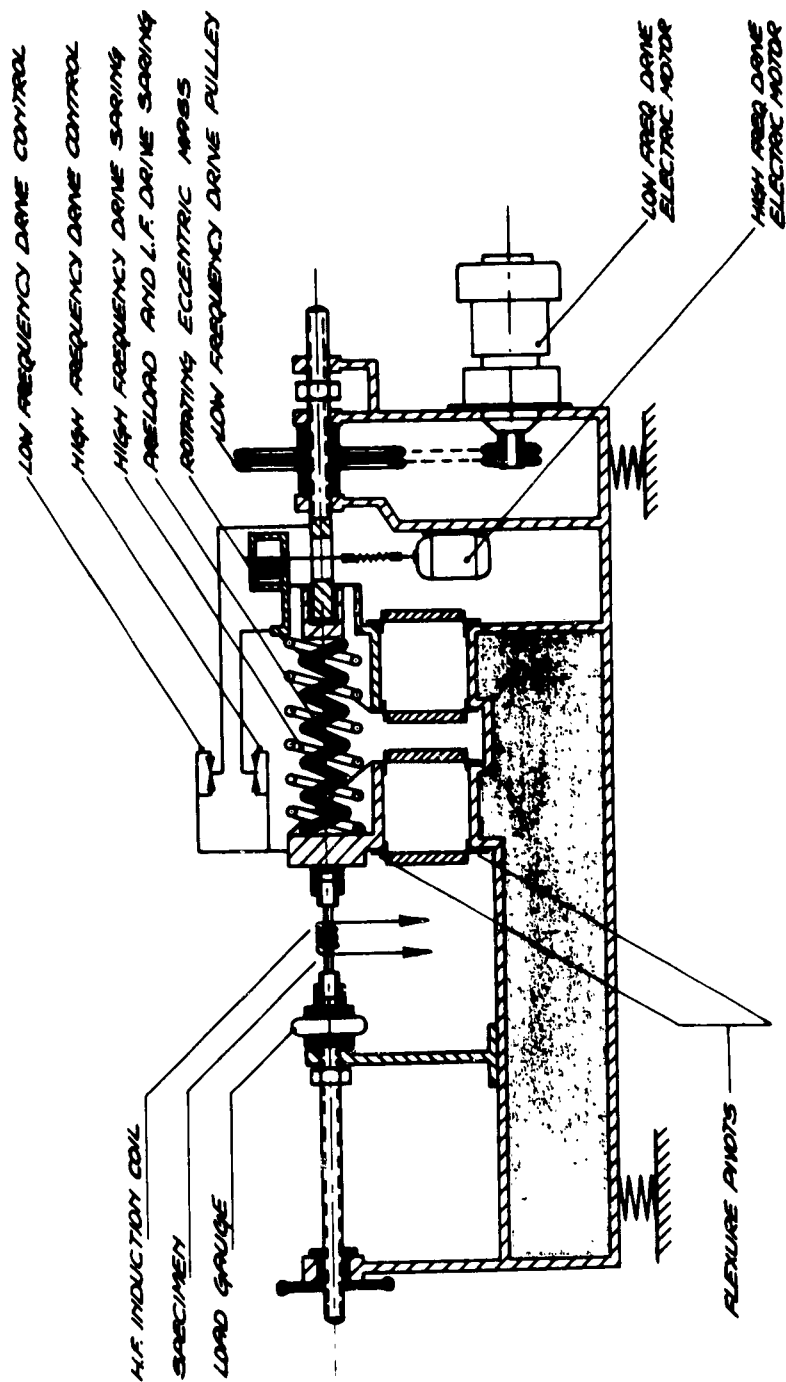


Fig. 7 Schematic diagram of Schenck-Erlinger pulsator equipped for testing at elevated temperatures

- F_1 : Main frame
 F_2 : Moving frame
 I_1 : Minimum load indicator
 I_2 : Maximum load indicator
 L : Load regulating mechanism
 M : Main cylinder
 P_1 : Immoveable palasetor cylinder
 P_2 : Swerving palasetor cylinder
 R : Rotating crank
 S : Specimen
 --- : Fluid suppletion line
 \odot : cock
 \square : valve

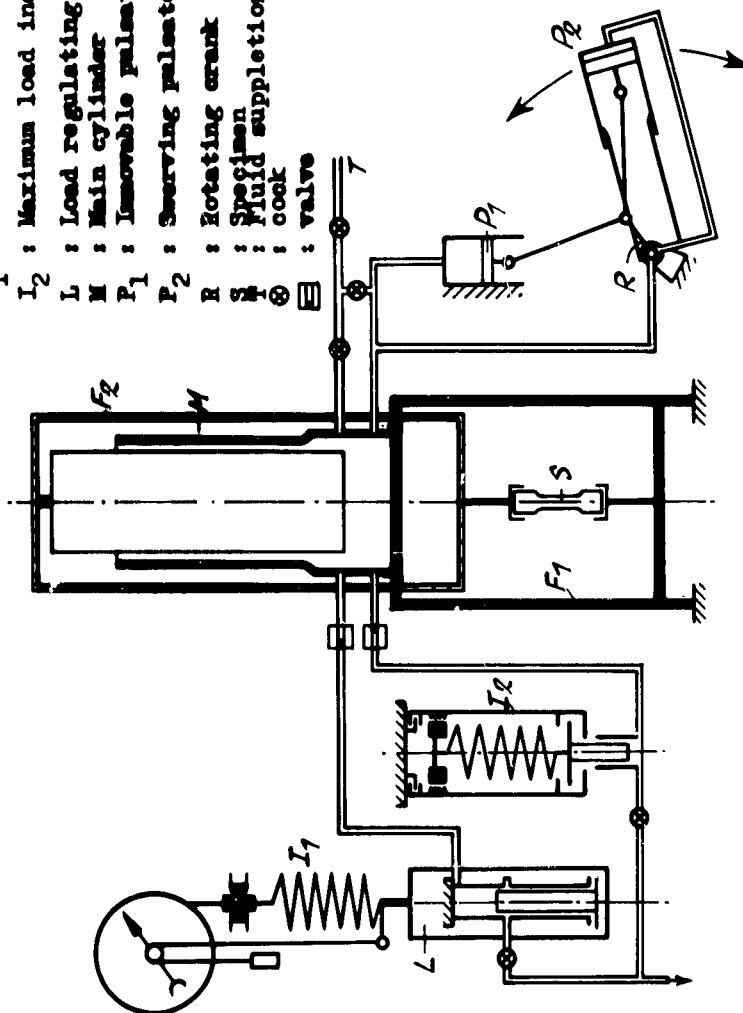


Fig. 8 Schematic diagram of Amsler hydraulic pulsator

- C - Compression cylinder
- E - Eccentric
- F₁ - Moving frame
- F₂ - Main frame
- M₁ - Minimum differential load manometer
- M₂ - Maximum differential load manometer
- M₃ - Pendulum load indicator
- P₁ - Hydraulic pump
- P₂ - Hydraulic pump
- S - Specimen
- T - Tension cylinder
- V - Variable stroke pulsator

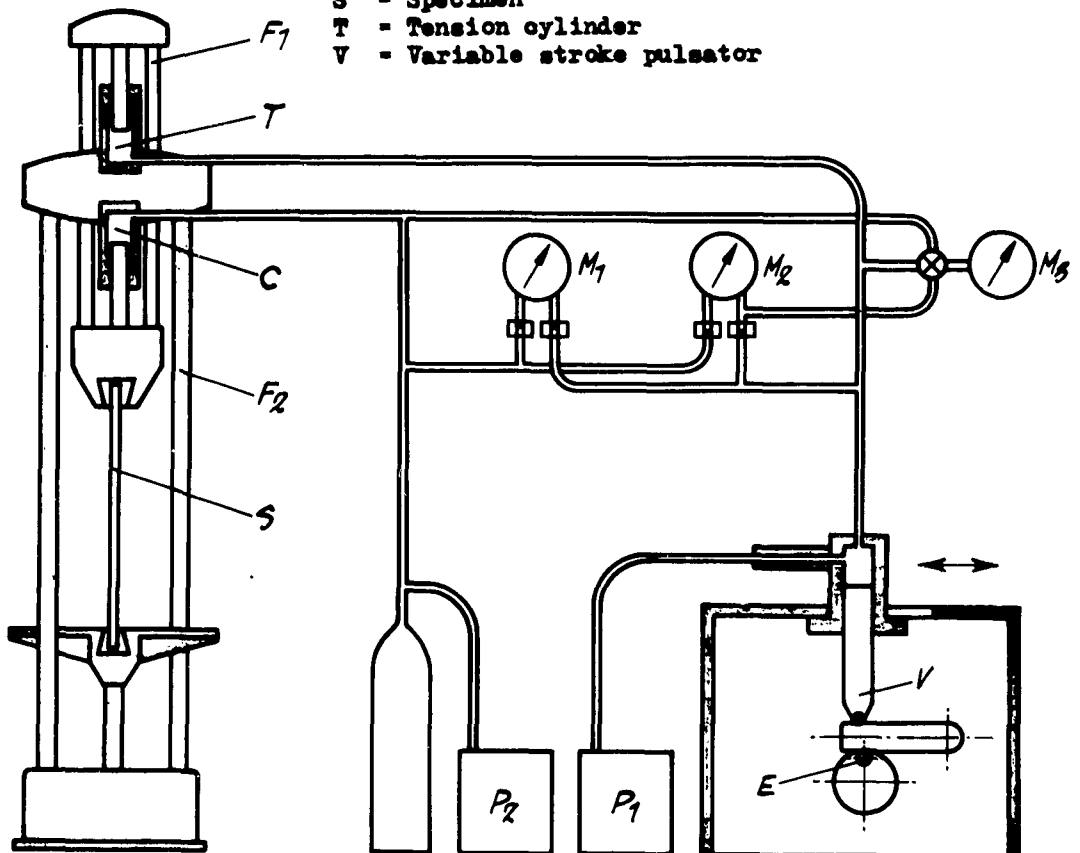


Fig.9 Schematic diagram of Losenhausen pulsator

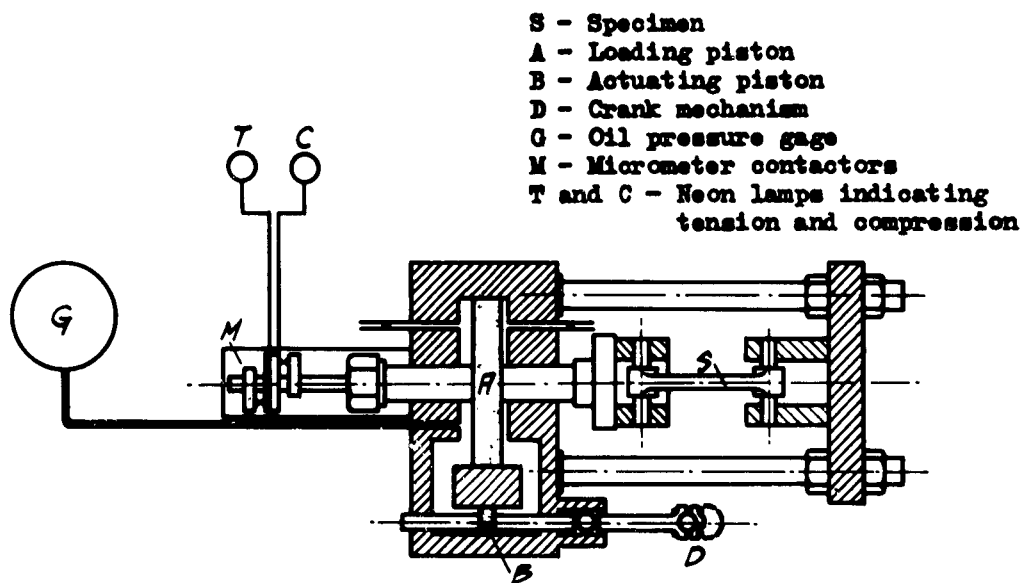


Fig.10 Schematic diagram of G.M.R. pulsator

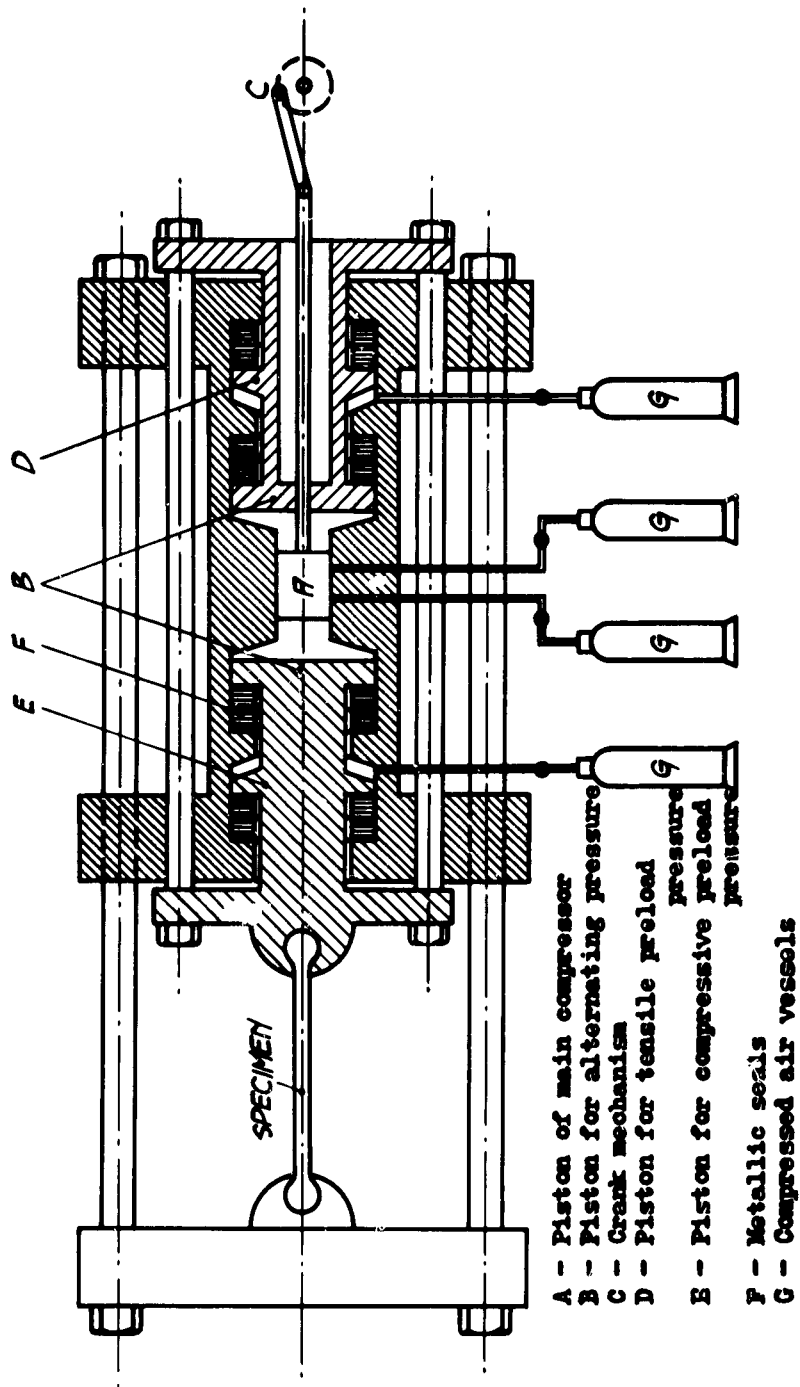


Fig.11 Schematic diagram of Lehr pneumatic fatigue machine

- C - Cylinder
- D - Dial gauge
- E - Casement
- F - Flexopulse cycle timer
- P - Piston
- PS - Pressure switch
- R - Piston rod
- S - Specimen
- T - Timer
- V - Solenoid valve

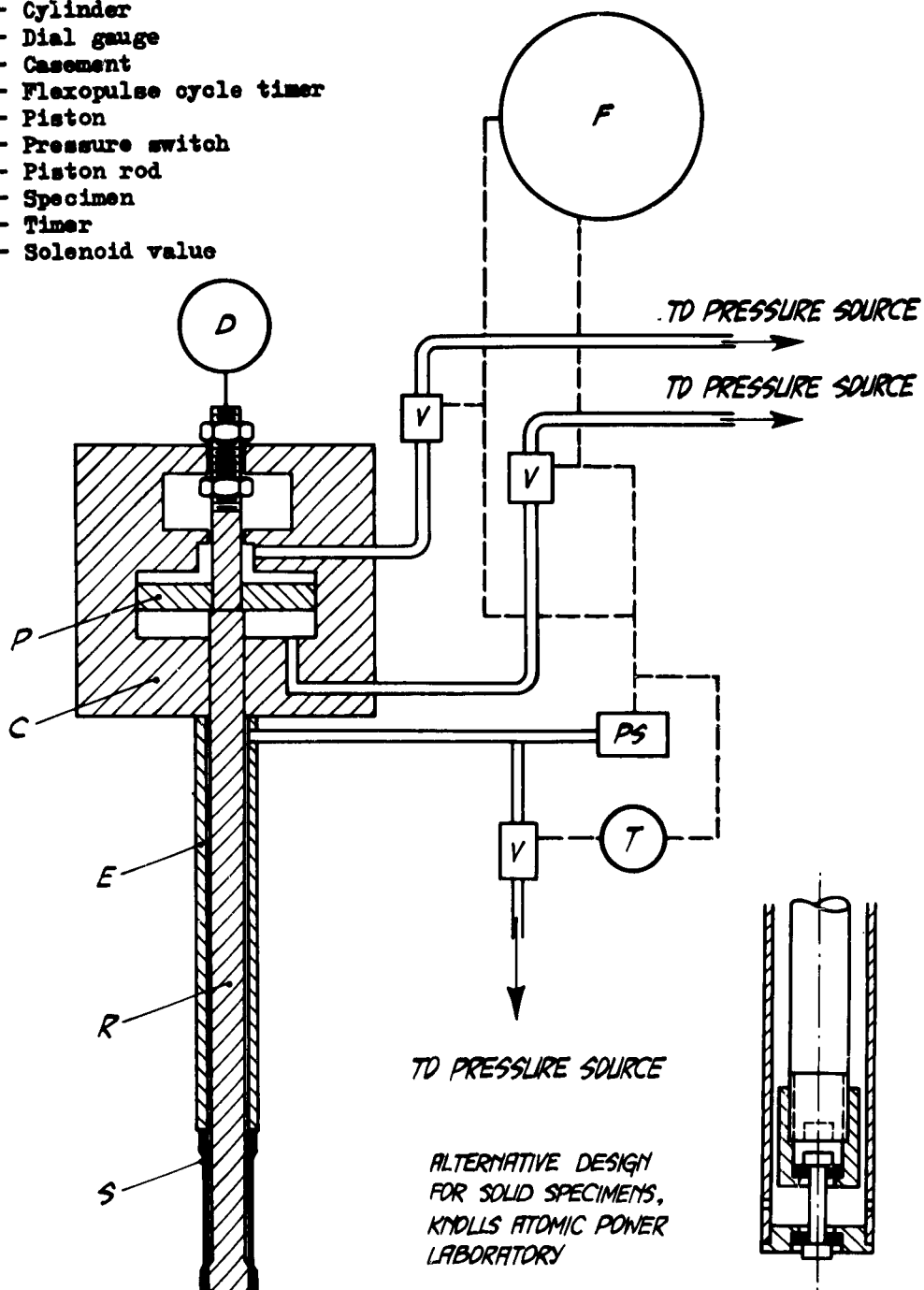


Fig.12 Schematic diagram of strain cycle apparatus, Oak Ridge National Laboratory

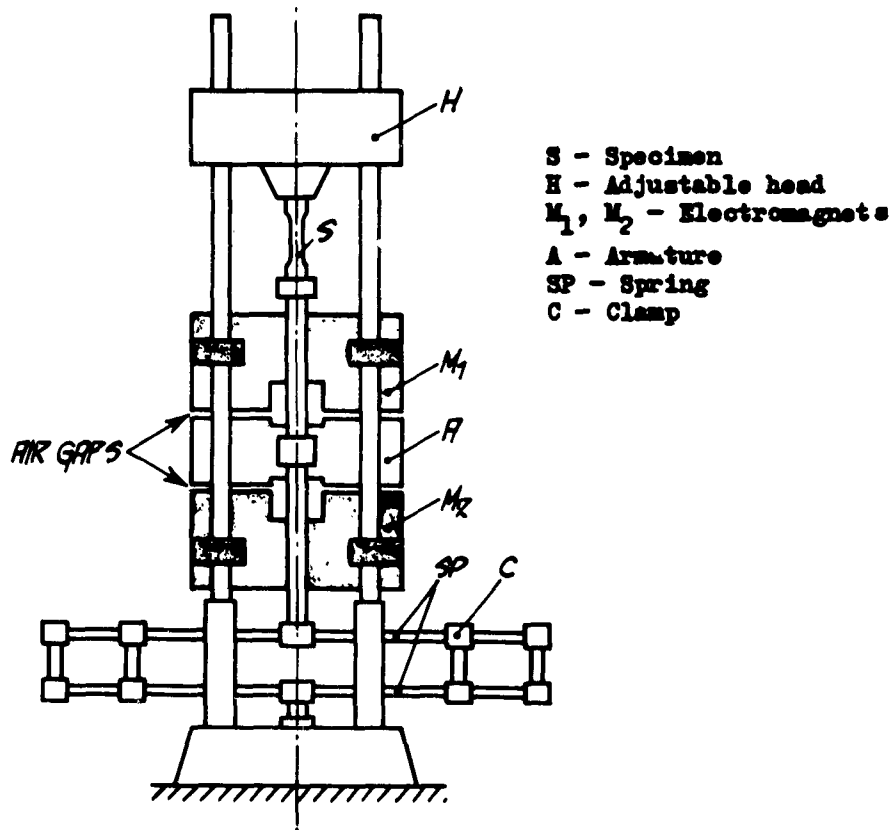


Fig.13 Schematic diagram of Haigh fatigue machine

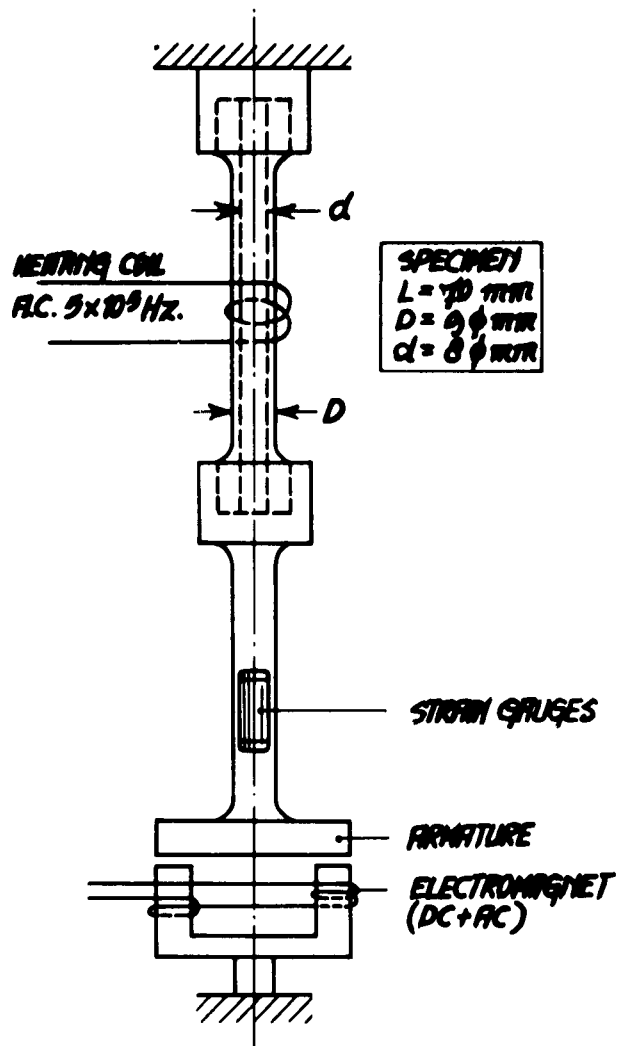


Fig.14 Schematic diagram of electromagnetic fatigue machine, Materials Laboratory, Malmslätt, Sweden

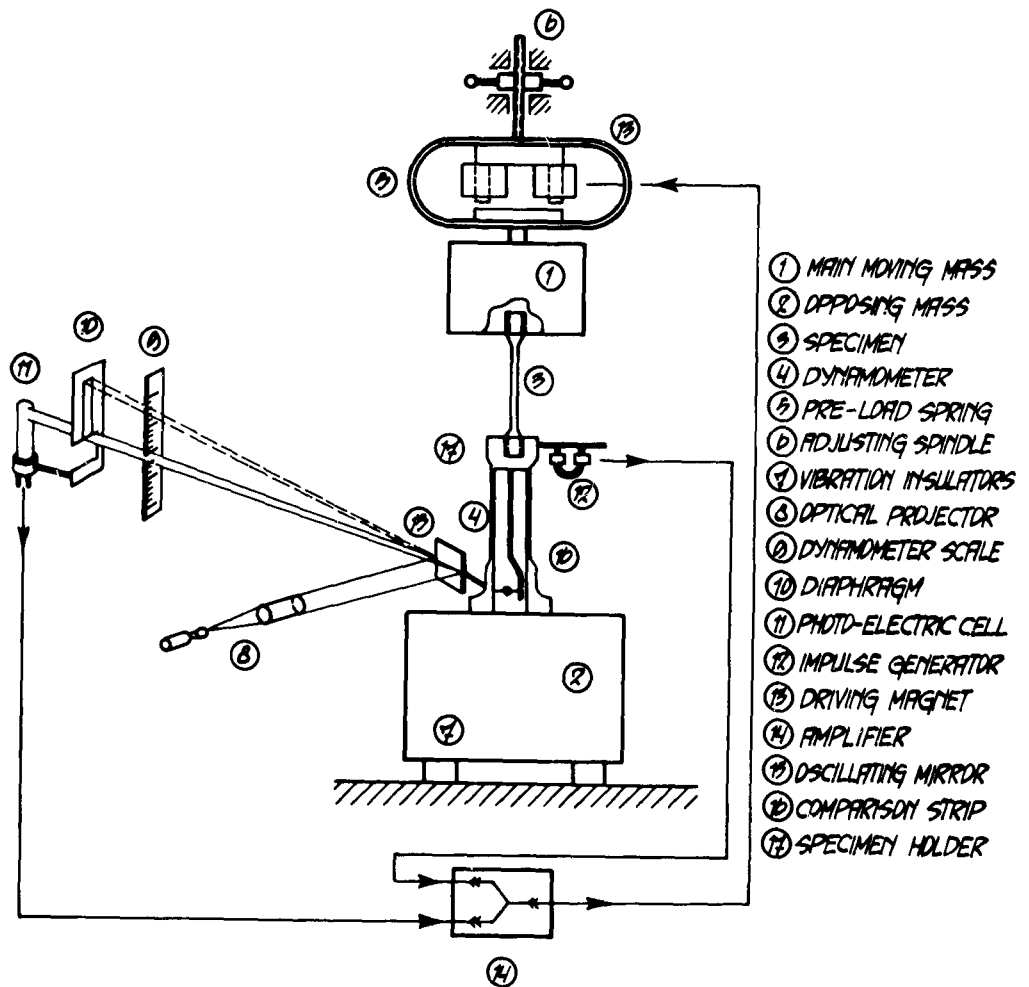


Fig.15 Schematic diagram of Amsler Vibraphore

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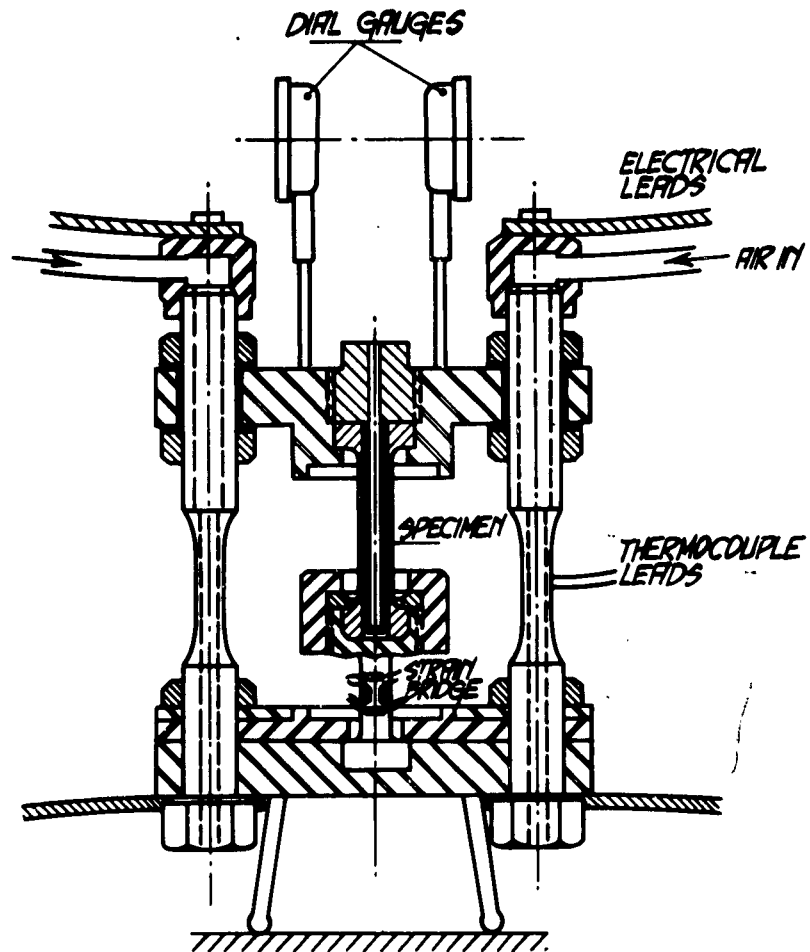


Fig.17 Schematic diagram of thermal expansion fatigue machine (parallel members heated), University of Alabama

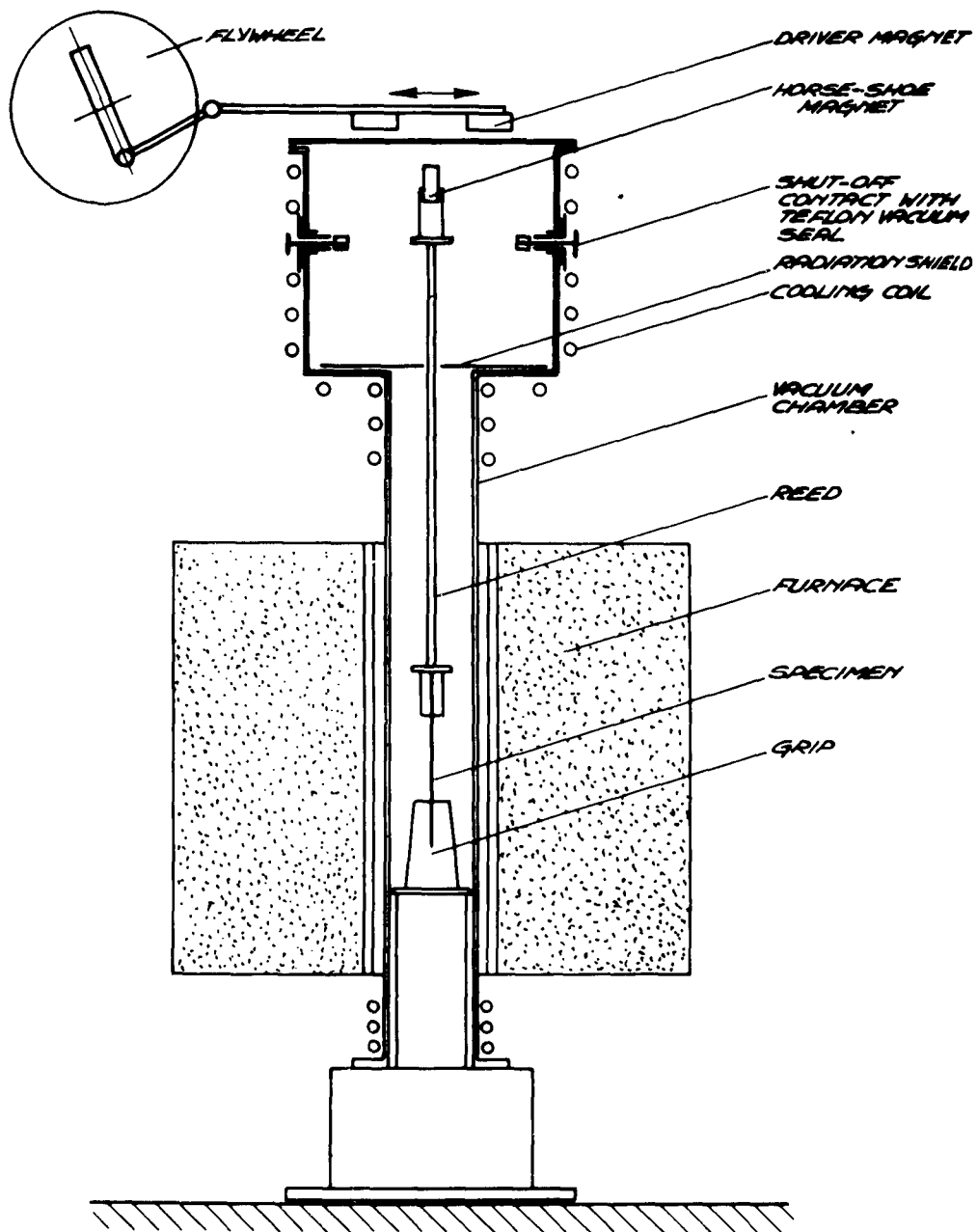


Fig.18 Schematic diagram of magneto-mechanical fatigue machine,
U.S. Naval Research Laboratory

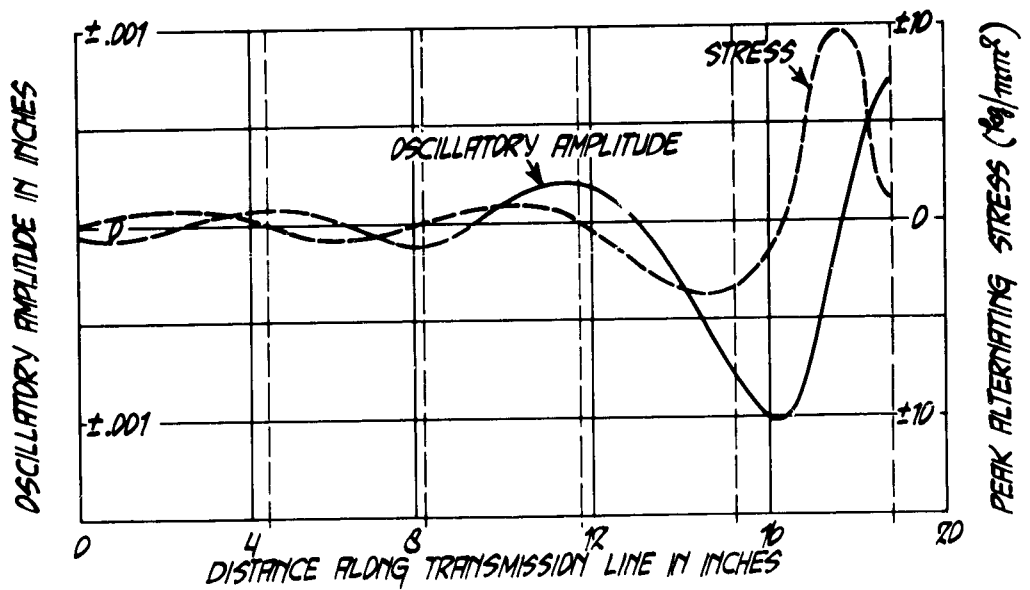
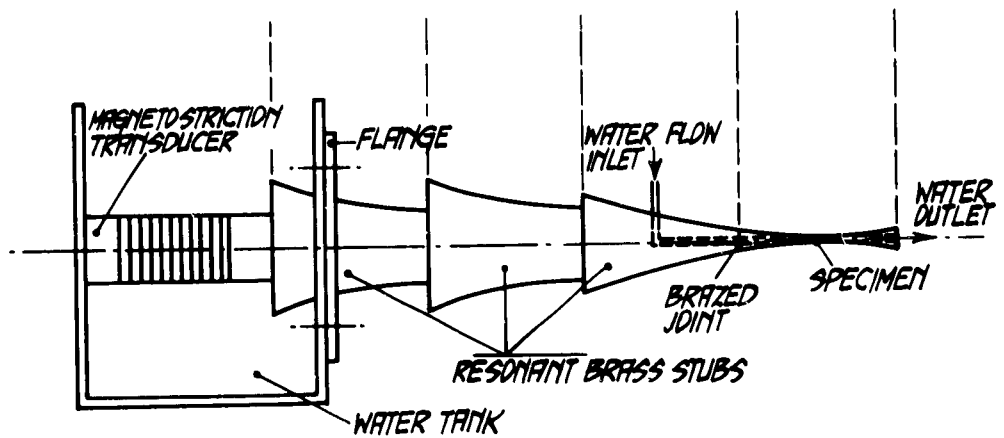


Fig. 19 Schematic diagram of magnetostriction fatigue machine and distribution curves of particle motion and stress in the mechanical transmission line

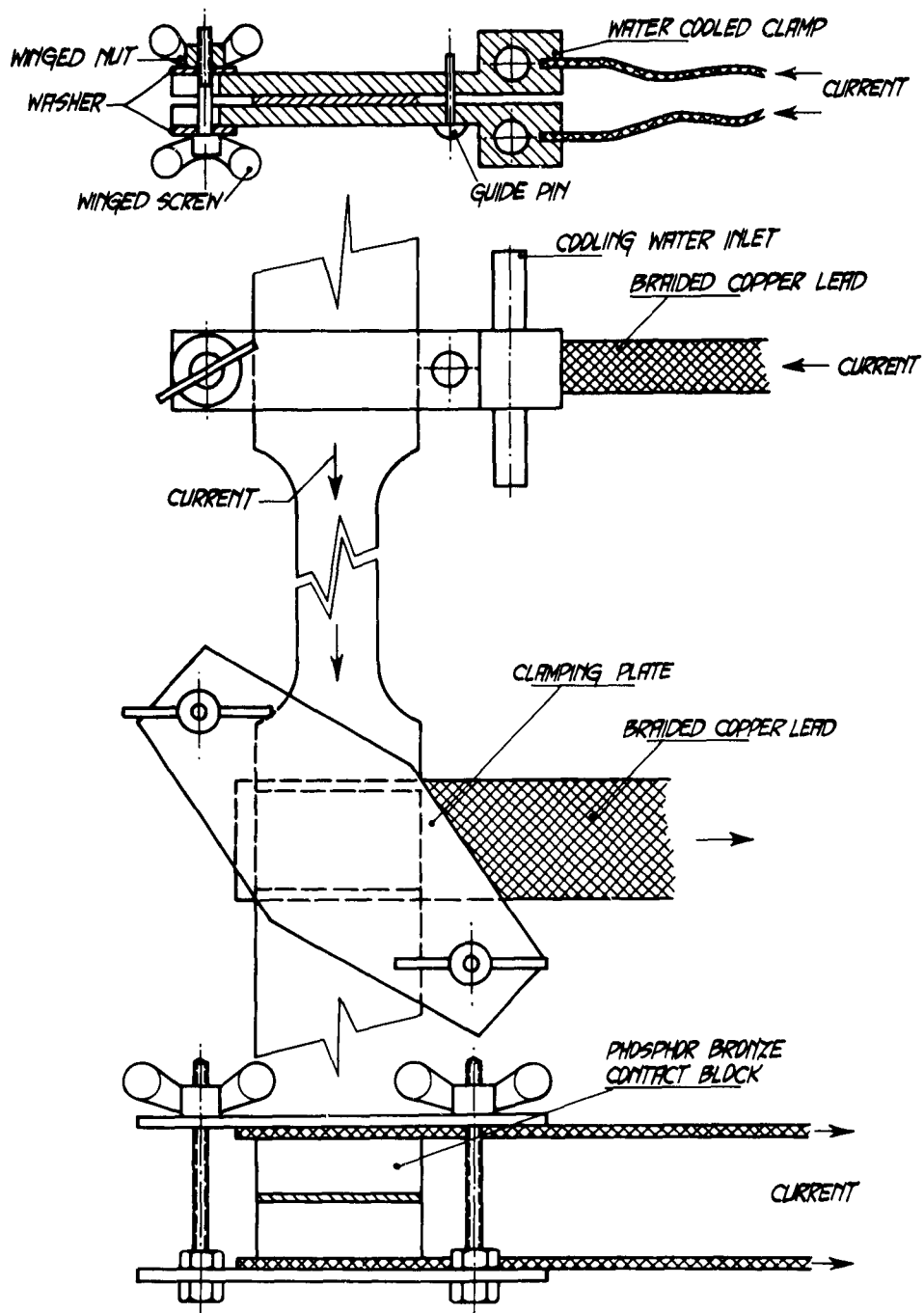


Fig.20 Direct electrical resistance heating, showing two examples of heating current connectors.

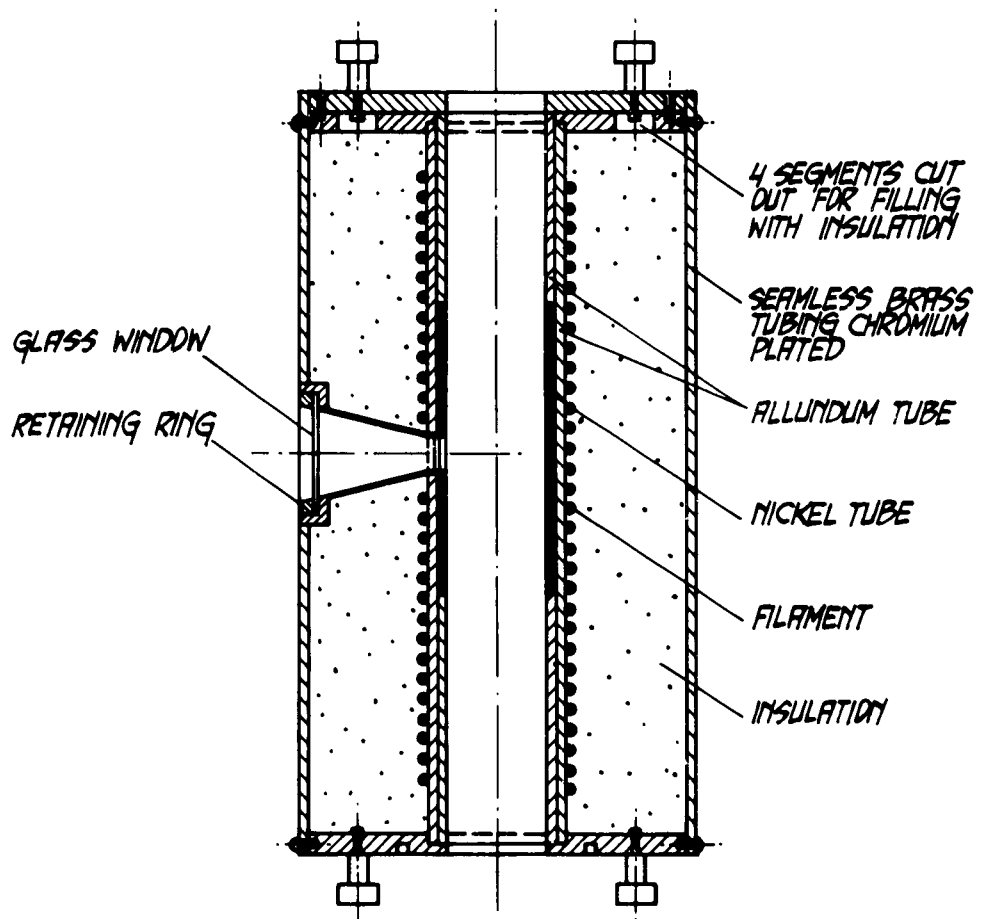


Fig.21 Wire-wound creep testing furnace

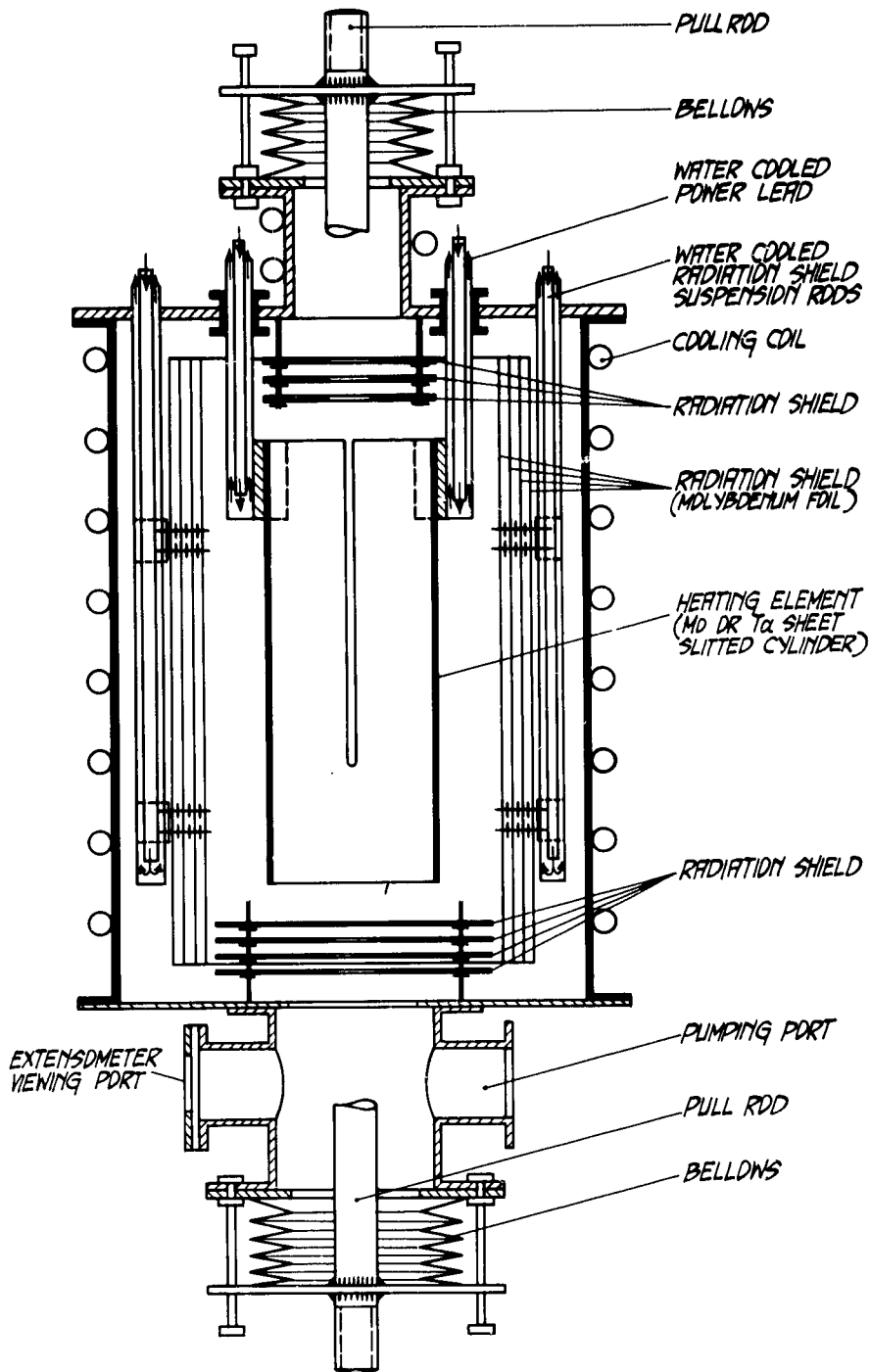


Fig.22 High temperature vacuum creep furnace

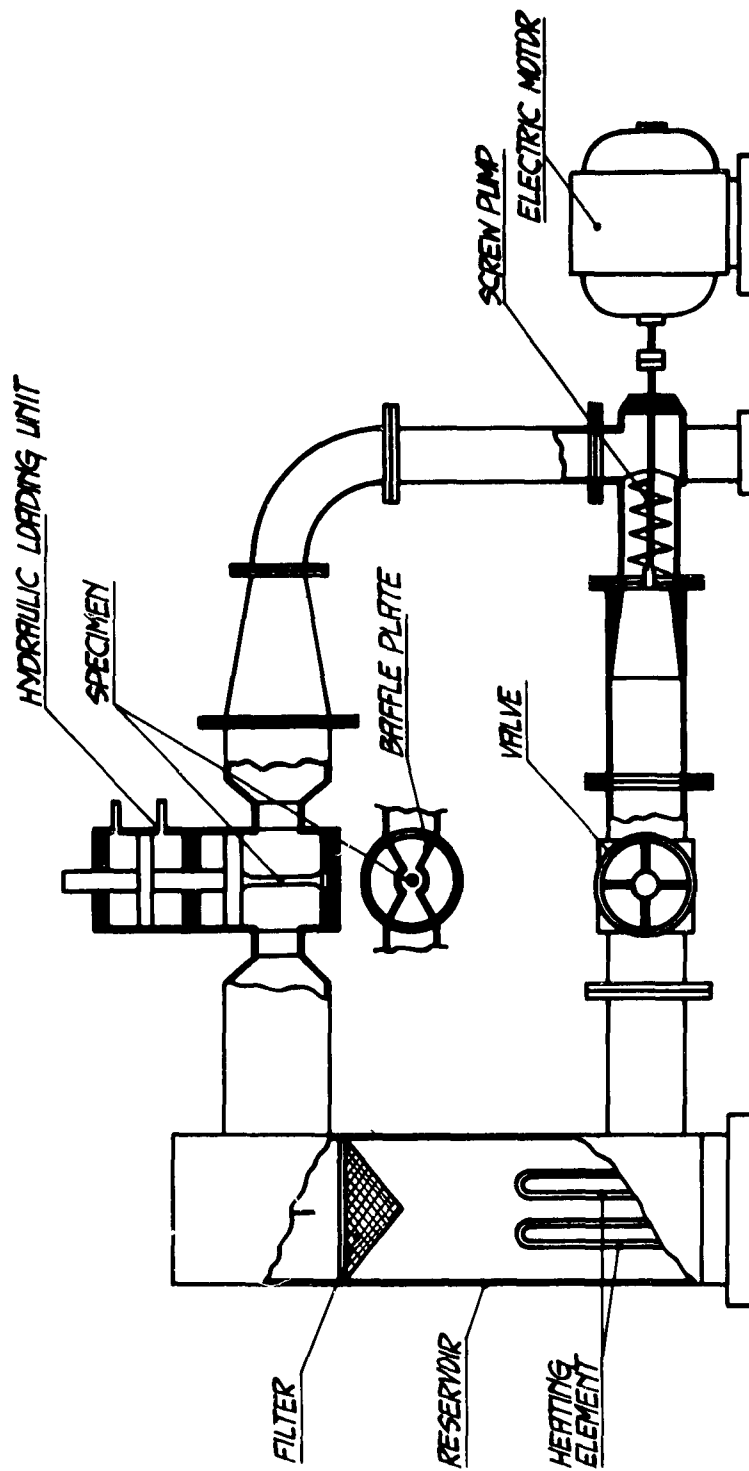


Fig. 23 Liquid atmosphere electrical resistance heater, Convair Pomona Division of General Dynamics Corporation

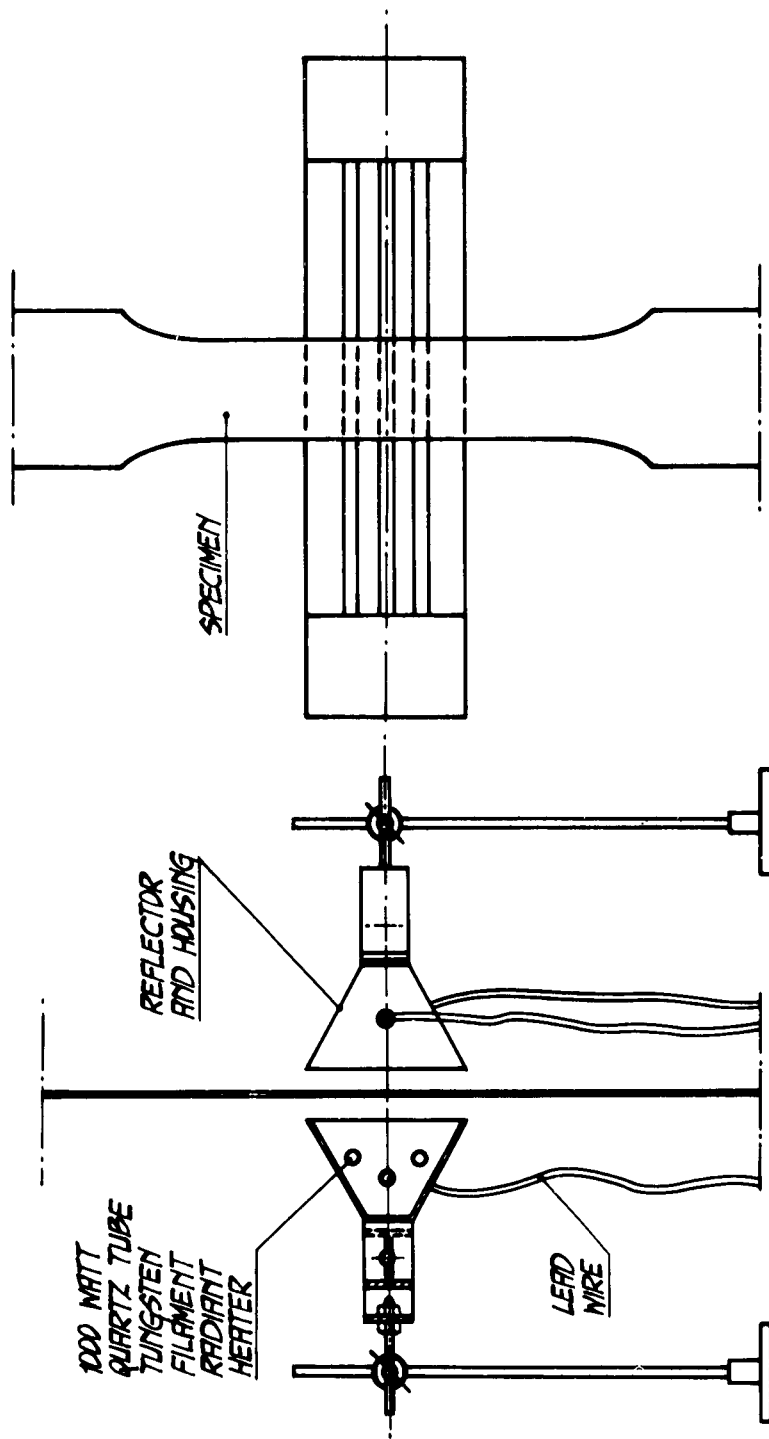


Fig.24 Radiant heater assembly

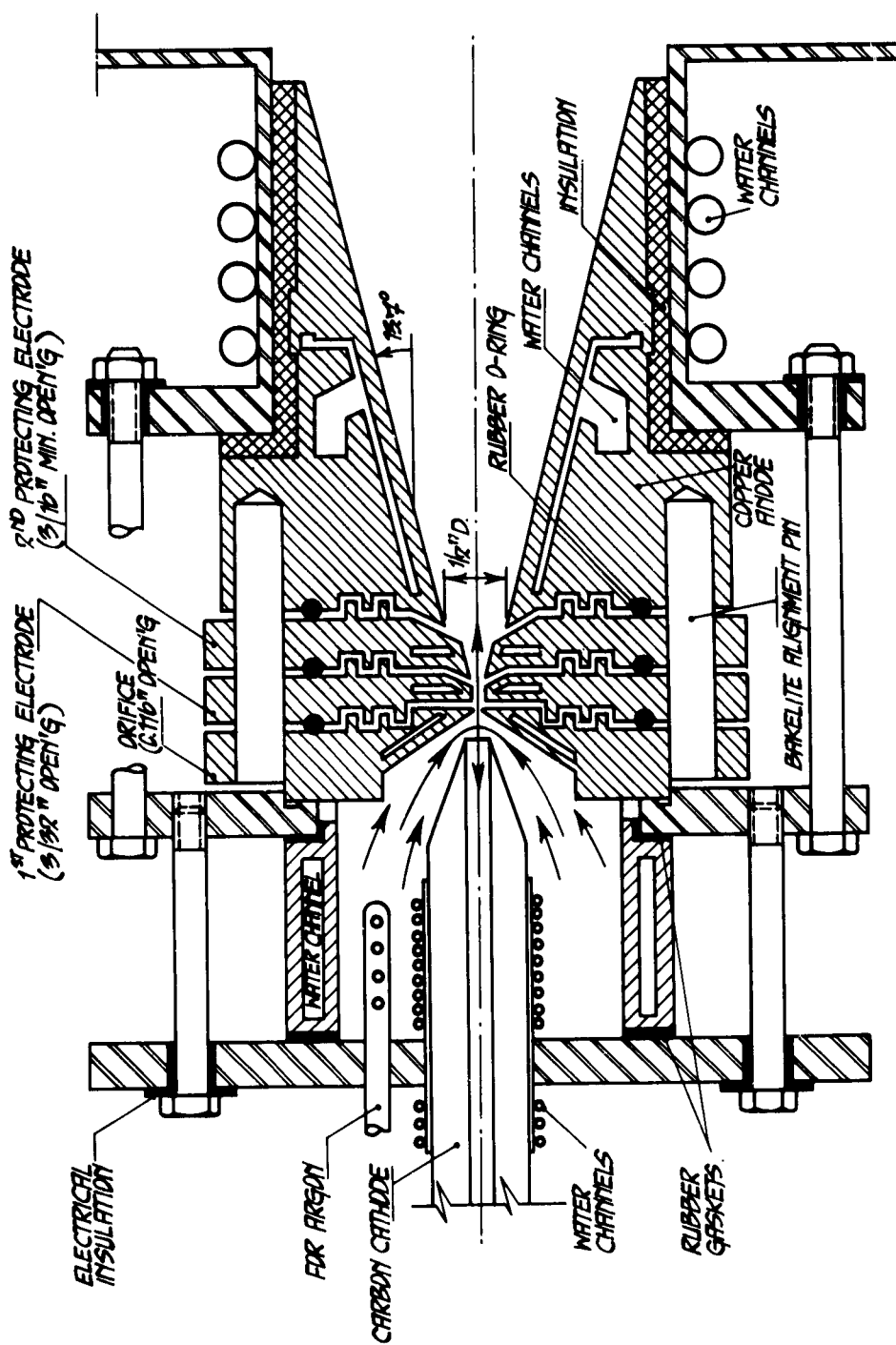


Fig. 25 Copper-carbon plasma jet, University of California, Institute of Engineering Research

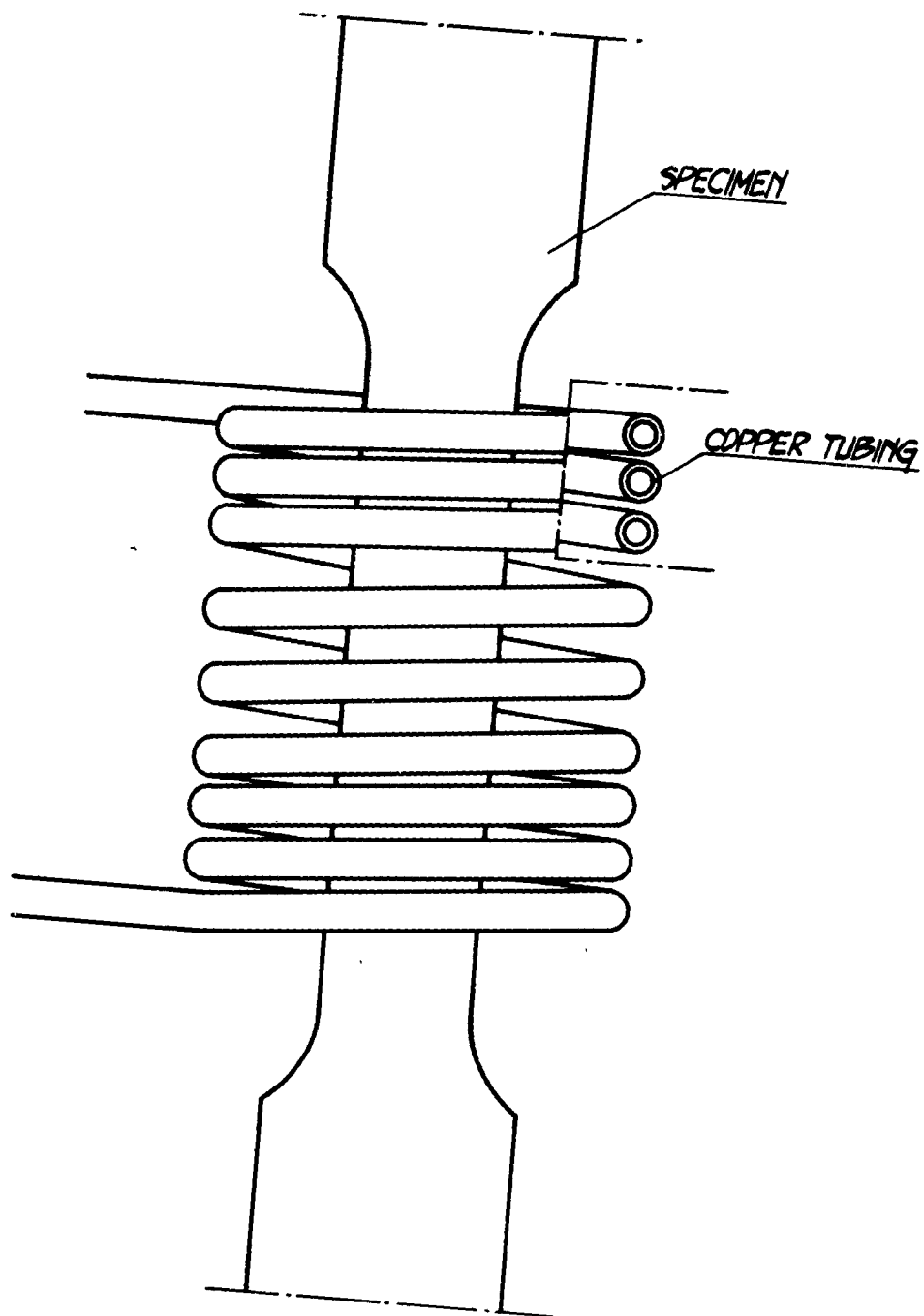


Fig.26 Helical water-cooled r.f. induction coil used by Watertown Arsenal Laboratory

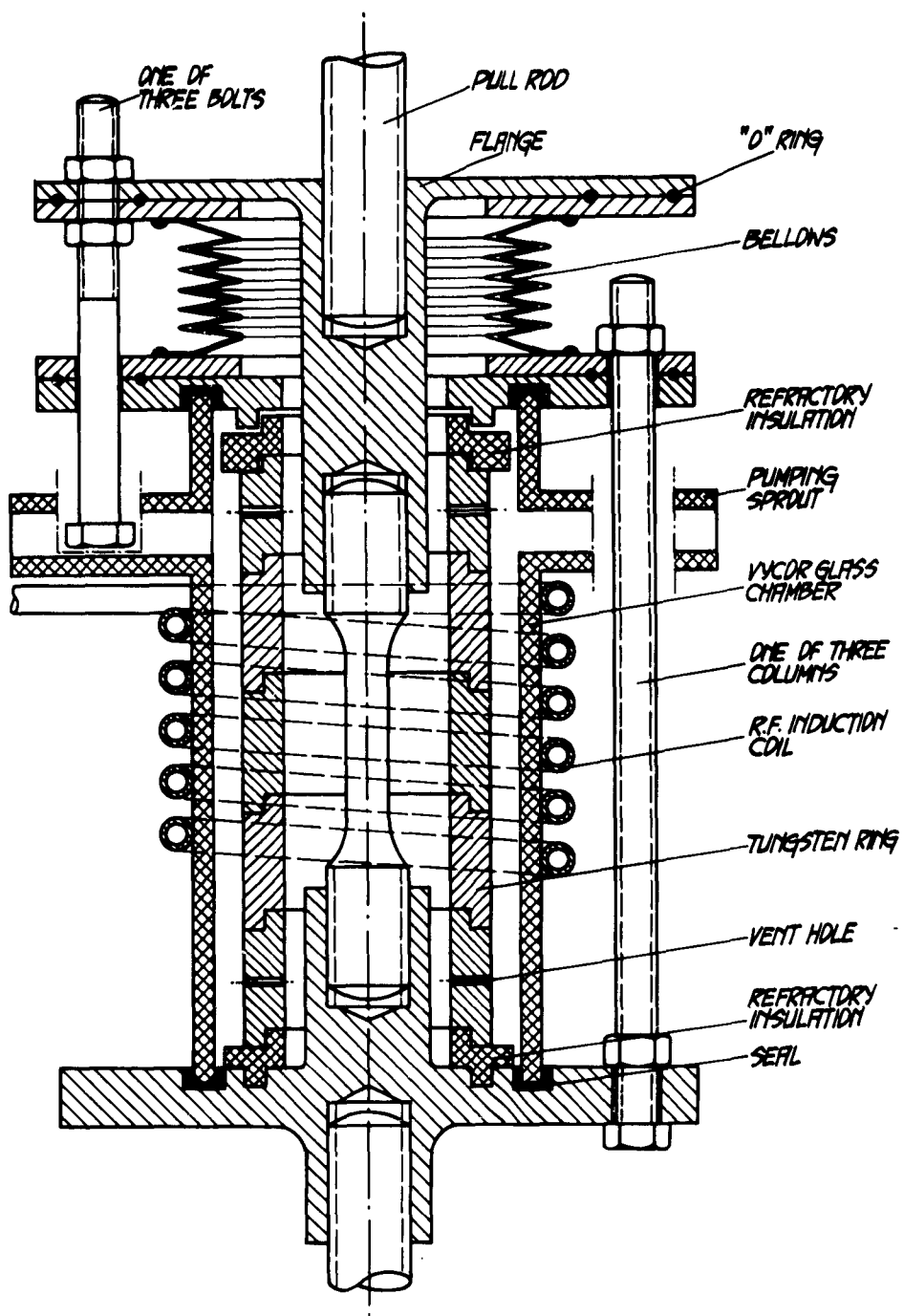


Fig. 27 Indirect r.f. induction heating with tungsten susceptor in controlled environment

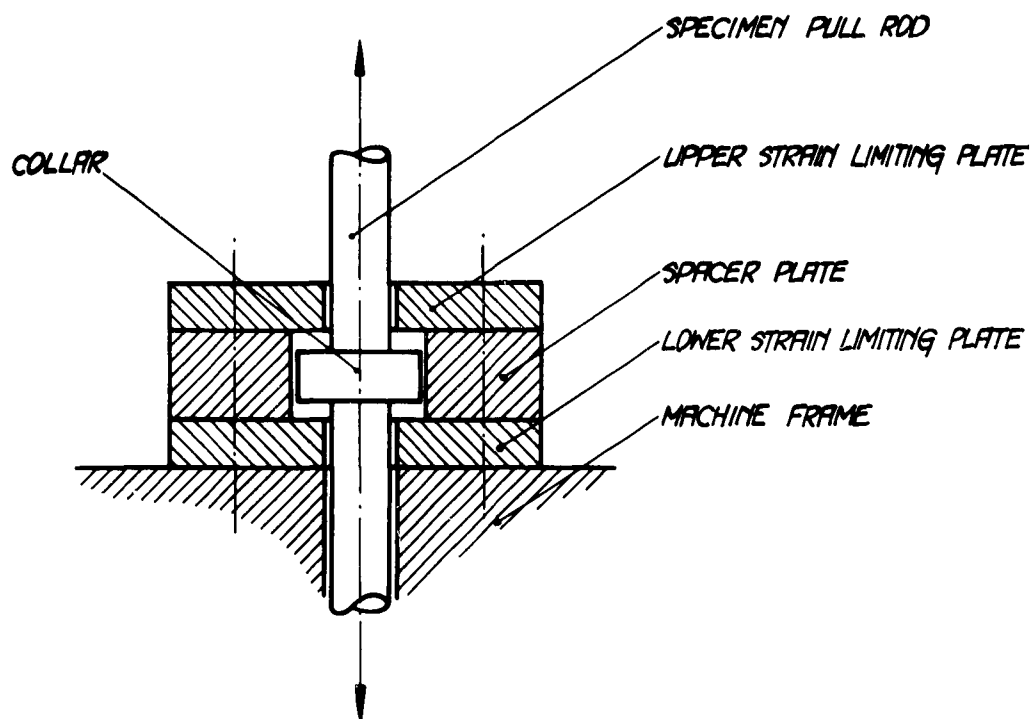


Fig.29 Schematic diagram of strain limiting device (Anderson and Waldron)

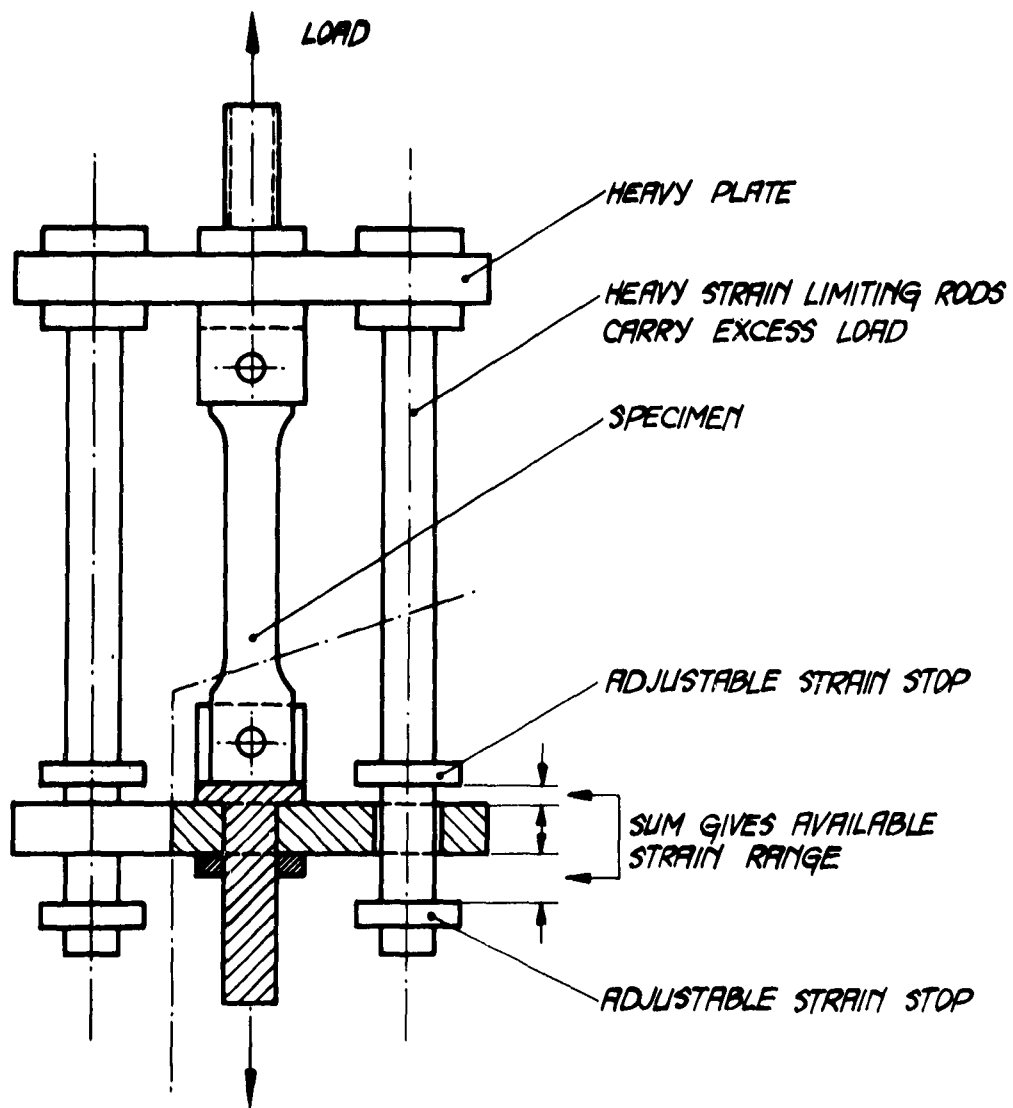


Fig.30 Strain limiting device for use in strain cycling at steady temperatures

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<p>AGARDograph 66 (Amended Edition) North Atlantic Treaty Organization, Advisory Group for Aeronautical Research and Development REQUIREMENTS FOR AN AXIAL FATIGUE MACHINE CAPABLE OF FAST CYCLIC HEATING AND LOADING H.P. van Leeuwen and Mahmut C. Mecdoglu 1961 23 pages incl. 59 refs., 6 Appendices incl. 30 figs.</p> <p>The object of the report was to investigate the requirements for an axial fatigue machine, capable of fast cyclic heating and loading. In order to evaluate the usefulness of existing equipment, various types of axial fatigue machines were studied with regard to the drive system, load</p> <p>P.T.O.</p>	<p>620.178.3 2b3g</p>	<p>AGARDograph 66 (Amended Edition) North Atlantic Treaty Organization, Advisory Group for Aeronautical Research and Development REQUIREMENTS FOR AN AXIAL FATIGUE MACHINE CAPABLE OF FAST CYCLIC HEATING AND LOADING H.P. van Leeuwen and Mahmut C. Mecdoglu 1961 23 pages incl. 59 refs., 6 Appendices incl. 30 figs.</p> <p>The object of the report was to investigate the requirements for an axial fatigue machine, capable of fast cyclic heating and loading. In order to evaluate the usefulness of existing equipment, various types of axial fatigue machines were studied with regard to the drive system, load</p> <p>P.T.O.</p>	<p>620.178.3 2b3g</p>
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